LOSSLESS COMPRESSION OF COLOR MOSAIC IMAGES

Ning Zhang and Xiaolin Wu
Department of Electrical and Computer Engineering, McMaster University
Hamilton, Ontario, Canada L8S 4K1
xwu@mail.ece.mcmaster.ca

ABSTRACT

We present a low complexity algorithm for lossless compression of color mosaic images generated by Bayer CCD color filter array. This algorithm is based on an interesting use of integer wavelet transform followed by a fast adaptive context-based Golomb-Rice coding. The lossless compression performance of the proposed algorithm is apparently the best reported in the literature so far for color mosaic images.

1. INTRODUCTION

Most digital cameras use image sensors that sample only one of the three primary colors at each pixel position. Specifically, each pixel is covered with a filter and records just one of the three primary colors: red, green or blue. These primary color samples are interleaved in a two-dimensional grid, or color mosaic, resembling a three-color checkerboard. To reconstruct the true continuous-tone color, a procedure called color demosaic is needed to interpolate the other two missing primary colors at each pixel. The image quality of digital cameras largely depends on the performance of the color demosaic process.

Image data compression is an important component of digital camera design and digital photography. It is more than just an issue of saving storage and bandwidth, but rather to be considered in light of overall system performance and functionality, particularly in relation to color demosaicking. Currently all digital cameras carry out color demosaicking prior to compression, apparently due to the considerations of easy user interface and device compatibility. However, industrial policy and standard issues aside, in our opinion, this design is suboptimal. Color demosaicking triples the amount of raw data by generating R, G, B bands via color interpolation. Ironically, the task of compression needs to decorrelate the three bands, which essentially attempts to reverse-engineer the color interpolation process of demosaicking. This increases algorithm complexity, reduces compression ratio, and burdens the on-camera I/O bandwidth.

In this paper we propose to compress and store the color mosaic data directly, and perform demosaicking to reconstruct the R, G, B bands afterwards, possibly off line. This relieves the camera from the tasks of color demosaicking and color de-correlation, and also reduces the amount of input data to compression codec in the first place. The new workflow can potentially reduce on-camera computing power and I/O bandwidth. More importantly, the new design allows lossless or near-lossless compression of raw mosaic data, which is the main theme of this paper.

For many high-end digital photography applications, such as archiving of museum arts, digital cinema, and professional advertising, for which high image quality is paramount, it is crucial to have the original color mosaic data coded lossless. Our research on color demosaicking [1] indicates that superior image quality can be obtained by more sophisticated color demosaicking algorithms than those implemented on camera. This requires the preservation of the original color mosaic data.

Lossless compression of mosaic color images poses a unique and interesting problem of spectral decorrelation of spatially interleaved R, G, B samples. In this paper we examine a number of interband coding techniques for lossless coding of mosaic color images. Our focus is on reversible lossless spectral-spatial transforms that can remove statistical redundancies. The actual coding is left to current lossless compression standards such as JPEG-LS [2] and JPEG 2000 [3].

The presentation is organized as follows. Section 2 presents some de-interleaving coding schemes. In Section 3 we develop an alternative approach of compressing color mosaic images directly without de-interleaving the color bands. An interesting wavelet decomposition tree structure, which resembles the SPACL mode of JPEG 2000 standard, is found to be well suited for lossless coding of Bayer pattern mosaic data. Section 4 introduces a fast context-based Golomb-Rice coding scheme to compress transform coefficients. Section 5 presents experimental results.

0-7803-8554-3/04/$20.00 ©2004 IEEE.

2. DEINTERLEAVED COMPRESSION

Most digital cameras use CCD sensor arrays of Bayer pattern [4] (see Fig.1). A natural way of compressing Bayer pattern mosaic images is to first de-interleave the three color channels, and then code each of the three down-sampled color channels individually.

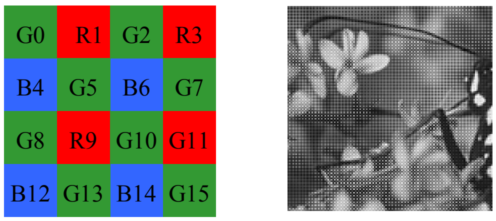


Fig. 1 Bayer pattern and an example of mosaic image

A general framework of de-interleaved compression can be designed as follows. We code the green channel before the other two channels, because the green channel has twice as many samples and hence higher correlation. Once the green samples are coded, we utilize the inter-channel correlation between the green and the other two channels to compress red and blue samples. To this end, we estimate the missing green values from the existing green samples at the pixel positions where either red or blue sample is taken. Denote such estimates by $\mathbf{g}$ to distinguish them from the existing green samples $\mathbf{G}$. Instead of coding $\mathbf{R}$ and $\mathbf{B}$ separately, we code the two color difference images $\boldsymbol{\alpha} = \mathbf{R} - \mathbf{g}$ and $\boldsymbol{\beta} = \mathbf{B} - \mathbf{g}$, which are much smoother than $\mathbf{R}$ and $\mathbf{B}$, and hence more amenable for predictive coding. Since the decoder can make the same estimates $\mathbf{g}$ as the encoder, it can reconstruct the original $\mathbf{R}$ and $\mathbf{B}$ from $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$.

In this general framework, there are two issues. First, the green channel is sampled in diamond grid (or so-called quincunx array), while existing image compression standards operate on square sample grid. We need to transform the green quincunx array to rectangular array before applying the existing lossless image compression algorithms. The second problem is how to estimate the missing green values from the existing green samples.

$$\begin{array}{cc} G_0 & G_2 \\ G_5 & G_7 \\ G_8 & G_{10} \\ G_{13} & G_{15} \end{array} \qquad \begin{array}{cccc} G_0 & G_2 & G_5 & G_7 \\ G_8 & G_{10} & G_{13} & G_{15} \end{array} \qquad \begin{array}{ccc} & G_0 & \\ G_8 & G_5 & G_2 \\ G_{13} & G_{10} & G_7 \\ & G_{15} & \end{array}$$

(a) Merging (b) Separation (c) Rotation

Fig. 2 Green channel transformation

There are four ways of de-interleaving the green samples from quincunx array to regular grid, as depicted in Fig. 2 (should be read in relation to Fig. 1) plus the reversible deinterlacer [5] [6]. Lossless coding can be performed on the de-interleaved green image(s). We found that the four deinterleaving methods affect the compression performance very little.

For the coding of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, we need to compute the estimates $\mathbf{g}$ of the missing green samples. Various interpolation schemes were evaluated, including bilinear interpolation, bi-cubic B-Spline [7] and some non-linear methods [8][9]. The simple bilinear interpolation works just as well as the more sophisticated schemes as far as compression is concerned. Table 1 presents lossless bit rates of JPEG-LS and JPEG 2000 lossless mode on the de-interleaved green channel (Fig.2a) and on the two color difference images $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ with $\mathbf{g}$ being produced by bilinear interpolation. For comparison we also give the results of coding red and blue channels directly without interband decorrelation. The color mosaic images were simulated by subsampling color test images (drawn from the ISO JPEG test and Kodak set) and interleaving the samples according to Bayer pattern (Fig.1a).

Table 1: Lossless bit rates of deinterleaved mosaic images by JPEG-LS and JPEG 2000.

	No interpolation		Bilinear interpolation	
Image	JPEG-LS	JPEG-2K	JPEG-LS	JPEG-2K
Woman	5.158	5.220	4.929	4.968
Bike	4.989	5.289	4.866	5.064
Monarch	4.447	4.613	4.323	4.448
KD01	5.967	6.152	5.766	5.855
KD06	5.153	5.323	4.980	5.085
KD08	6.186	6.388	5.998	6.086
KD13	6.482	6.697	6.256	6.406
KD19	5.080	5.154	4.909	4.926
KD21	5.000	5.161	4.863	4.96
Ave.	**5.384**	**5.555**	**5.210**	**5.311**

It is clear from Table 1 that coding color differences is more effective than coding the red and blue channels individually. JPGE-LS achieves better compression than JPEG 2000.

3. INTERLEAVED COMPRESSION

An alternative approach to lossless compression of color mosaic images is to process the mosaic data directly without de-interleaving the color channels. This has the advantage of simpler design and lower complexity. One way is to apply a lossless image coding algorithm directly to raw color mosaic images without any preprocessing.

Table 2 lists the lossless bit rates of the test images by JPEG-LS and JPEG 2000 lossless mode (the 5-3 integer filter is used). Interestingly, JPEG-2000 significantly outperforms JPEG-LS in the case of compression of interleaved data by a large margin (more than 10%). Recall from the proceeding section that the performance comparison between the two algorithms in the case of de-interleaved compression gave exactly opposite results. This reversal in relative coding efficiency is largely due to a fundamental difference in decorrelation mechanisms of the two algorithms: DPCM for JPEG-LS and lifting integer wavelet of JPEG 2000. The DPCM scheme is designed to remove long term memory of a smooth signal, whereas the wavelet, being a tool of frequency-time analysis, can compactly characterize regular patterns such as those in color mosaic.

Our comparison study verifies that JPEG 2000 (in its lossless mode) can be conveniently applied to lossless compression of Bayer pattern mosaic images. The good performance of the 5-3 integer wavelet on mosaic images can be well explained by a model of mosaic images that is developed for color demosaicking purpose [1]. Bayer pattern mosaic images can be viewed as a sum of two images as illustrated below

$$\begin{matrix} G_0 & R_1 & G_2 & R_3 \\ B_4 & G_5 & B_6 & G_7 \\ G_8 & R_9 & G_{10} & R_{11} \\ B_{12} & G_{13} & B_{14} & G_{15} \end{matrix} = \begin{matrix} G_0 & G_1 & G_2 & G_3 \\ G_4 & G_5 & G_6 & G_7 \\ G_8 & G_9 & G_{10} & G_{11} \\ G_{12} & G_{13} & G_{14} & G_{15} \end{matrix} + \begin{matrix} 0 & \alpha_1 & 0 & \alpha_3 \\ \beta_4 & 0 & \beta_6 & 0 \\ 0 & \alpha_9 & 0 & \alpha_{11} \\ \beta_{12} & 0 & \beta_{14} & 0 \end{matrix}$$

The first image is the full resolution green channel. The other is a checker board sampled color difference image: $\alpha_i = R_i - G_i$, $\beta_i = B_i - G_i$.

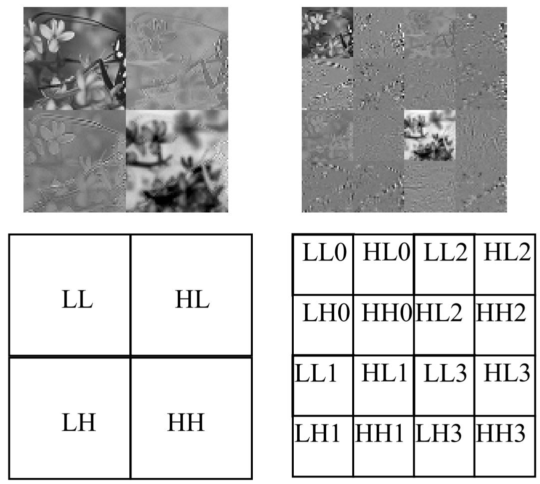
An integer wavelet transform is approximately a linear operation, if we ignore the rounding. Applying wavelet transform directly to a mosaic image is roughly equivalent to transforming the full resolution green channel and the down sampled color difference image separately and then adding the results together. Now let us examine the outcome of such an operation. Applying the two dimensional 5-3 high-pass filter:

$$\frac{1}{4}\begin{bmatrix} 1 & -2 & 1 \\ -2 & 4 & -2 \\ 1 & -2 & 1 \end{bmatrix}$$

to, say, position G_5 yields

$$w_{G5} = \left[G_5 - \frac{1}{2}(G_1 + G_4 + G_6 + G_9) + \frac{1}{4}(G_0 + G_2 + G_8 + G_{10}) \right] - \frac{1}{2}(\alpha_1 + \alpha_9 + \beta_4 + \beta_6)$$

The first term is the usual HH band details of green channel. The second term is low pass filtered color difference. Difference image $\mathbf{\alpha} = \mathbf{R} - \mathbf{g}$ is averaged vertically; and $\mathbf{\beta} = \mathbf{B} - \mathbf{g}$ is averaged horizontally. Since color difference images $\mathbf{\alpha}$ and $\mathbf{\beta}$ are mainly low passed signals in the first place, the 5-3 high-pass filter actually (or quite counter-intuitively) makes their HH response even smoother. In other words, the 5-3 high-pass filter has the effect of inter-band decorrelation. In summary, the HH subband of a Bayer mosaic image contains the details of the green channel and a highly smoothed color difference signal (see Fig.3a). If we apply the 5-3 integer wavelet transform again (Fig.3b) to HH band we achieve greater energy compaction by further separating the green details from the smooth color difference signal. .



(a) one level (b) two levels

Fig. 3 Wavelet transform of a Bayer mosaic image.

Similar analysis can be applied to other subbands. After two levels of packet wavelet transform, we get the sixteen subbands as in Fig.3b. The LL0 subband contains down sampled luminance information, the energy of the color difference signal is packed into the LL1, LL2 and LL3. The other twelve subbands contain the much of image details.

4. FAST CONTEXT-BASED COEFFICIENT CODING

Based on the above analysis, one can directly apply JPEG 2000 using the options of 5-3 integer wavelet and the SPACL decomposition (two-level SPACL is equivalent to wavelet packet in Fig.3b) for lossless coding of color mosaic images. However, to achieve on-camera real-time lossless encoding of mosaic images, we propose a much simpler and faster solution than JPEG 2000.

We advocated the use of wavelet packet transform of two levels with the 5-3 interger filter for the purpose of energy packing of the original mosaic image. As we saw in Fig.3b this transform effectively de-correlates the mosaic data both in the spatial (image) and spectral (color) domains. The integer transform coefficients will be coded by a simple context-based Golomb-Rice coding scheme to be developed below.

Coefficients in each subband are coded in raster scan order from left to right and top to bottom. The L-shape causal neighborhood:

$$\begin{matrix} X_{nw} & X_n & X_{ne} \\ X_w & X & \end{matrix}$$

is used to code the current coefficient X in the four smooth subbands: LL1, LL2, LL3, LL4. A simple linear prediction is performed as:

$$\hat{X} = \frac{1}{2}(X_n + X_w) + \frac{1}{4}(X_{ne} - X_{nw})$$

The prediction error $e = X - \hat{X}$ is mapped from a signed integer into a non-negative integer

$$E = \begin{cases} 2e & X \geq \hat{X} \\ -2e-1 & X < \hat{X} \end{cases}$$

and then coded by Rice code. The Rice parameter is determined by the prediction error energy in the L-shape context:

$$\Delta = \sum_{j \in \{w,nw,n,ne\}} \left| X_j - \hat{X}_j \right|$$

The Rice parameter is set to

$$k = \arg_j \{T_j \leq \Delta < T_{j+1}\}.$$

The thresholds $\{T_j\}$ can be optimized to minimize the Rice code length by offline dynamic programming. We found empirically the following simple thresholds

$$T[0:9] = \{0,2,8,16,32,64,128,256,512,+\infty\}$$

work well on 8 bit mosaic images (within less than 2% from the minimum achievable Rice code length by dynamic programming).

The remaining twelve high frequency subbands are coded similarly, however without the prediction step since the wavelet coefficients in those subbands are themselves prediction residuals (the lifting scheme of the 5-3 integer wavelet serves as a predictor).

Table 2 presents the lossless bit rates of different methods when applied directly to raw mosaic images of Bayer pattern. The proposed method, despite its simplicity, outperforms all other methods on each test image. The average bit rate of the proposed interleaved compression method also outperforms the best de-interleaved coding results of JPEG-LS in Table 1, although JPEG-LS uses a more complex on-line context modeling technique.

Table 2: Lossless bit rates of mosaic images by JPEG-LS, JPEG 2000 and proposed method

Image	JPEG-LS	JPEG 2000		Proposed
		Default	SPACL	
Woman	5.592	4.943	4.913	**4.876**
Bike	5.791	5.045	5.035	**4.908**
Monarch	7.216	4.893	4.528	**4.377**
KD01	6.398	5.809	5.762	**5.65**
KD06	5.862	5.207	5.117	**5.028**
KD08	6.286	5.895	5.892	**5.725**
KD13	6.735	6.368	6.387	**6.243**
KD19	5.47	4.907	4.867	**4.823**
KD21	5.469	5.034	4.958	**4.867**
Ave.	**6.091**	**5.345**	**5.273**	**5.166**

5. CONCLUSION

Various techniques for lossless coding of raw color mosaic images generated by CCD cameras of Bayer pattern were investigated. It turned out that the integer wavelet transform is ideally suited to the task, by offering efficient energy packing in both image and color spaces. A fast and practical codec for lossless compression of mosaic images was developed.

6. REFERENCES

[1] X. Wu and N. Zhang, "Primary-consistent soft-decision color demosaicking for digital cameras", *IEEE Trans. on Image Processing* (to appear).

[2] ISO/IEC JTC1/SC29/WG1, "Information technology – Lossless and near-lossless compression of continuous-tone still images," ISO FDIS 14495-1(JPEG-LS), also ITU Recommendation T.87, 1998.

[3] ISO/IEC JTC1/SC29/WG1 Document N1890 "JPEG 2000 Part I Final Draft International Standard", 2000

[4] B. Bayer, "Color imaging array", U.S. Patent 3,971,065.

[5] K. Hisakazu, M. Shogo, T. Ishida, T. Kuge, "Reversible conversion between interlaced and progressive scan formats and its efficient implementation", EUSIPCO 2002, Paper 448, Sept. 2002

[6] C.C. Koh and S.K. Mitra, "Compression of Bayer Color Filter Array Data", ICIP 2003

[7] D.R. Cok, "Signal processing method and apparatus for sampled image signals" U.S. Patent 4,630,307, 1987

[8] R.H. Hibbard, "Apparatus and method for adaptively interpolating a full color image utilizing luminance gradients", US patent 5382976, 1995.

[9] O. Rashkovskiy and W. Macy, "Method of determining missing color values for pixels in a color filter array", US patent 6181376, 2001.