Computation-Efficient Image Signal Processing for CMOS Image Sensors

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Abstract - *This paper presents an efficient image signal processing method proposed for CMOS image sensors. In the proposed method, the color correction is moved to the front of the color demosaic to reduce the arithmetic complexity required in the color correction to one third, and a new color correction method is suggested to achieve good images with less data. In spite of the reduced complexity, experimental results show that the peak-signal-to-noise ratio is increased by 0.59dB compared to the conventional method.*

Keywords: CMOS image sensors, image processing, image enhancement, color correction.

1 Introduction

Imaging systems have been experiencing explosive growth in recent years due to the increasing demands for multimedia applications such as digital still and video cameras. In these applications, the charge-coupled devices (CCDs) have been widely used as a part of image acquisition systems. Due to the benefits of CMOS image sensors (CISs) such as low cost, low power and high integration [1], CISs are rapidly replacing CCDs. On the other hand, the image quality of CISs is not as good as that of CCDs because CISs generally suffer from high read noise, high fixed pattern noise and inferior photo-detectors due to the imperfections of CMOS processes [2]. In addition, typical image sensors provide images containing only one color information per pixel. Therefore, several image signal processings are needed to enhance the image quality. As CISs are widely adopted in portable applications and the resolution is increasing tremendously, area and power consumption are crucial factors to be seriously considered in practical implementations.

In the conventional image signal processing [3]–[5], the color demosaic process is performed first to derive missing color components by interpolating the color components using neighbor pixels. The rest processings deal with the three color components on each pixel. If some processing steps can be performed before the color demosaic, it is possible to reduce the amount of data to be computed, leading to reduced computational complexity and power consumption. In this letter we propose a new image signal processing method for CISs to reduce the computational complexity without sacrificing image quality.

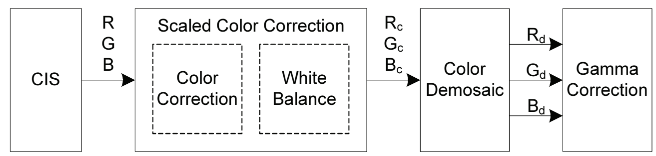

Figure 1. Conventional CIS image signal processing

2 Conventional Image Signal processing for CMOS Image Sensors

The typical image processing includes color demosaic, color correction, white balance, gamma correction, etc. The image processing has two major objectives. One is to reconstruct missing color components, and the other is to produce color on a display device that is close to what the eye would perceive. Figure 1 shows the conventional image signal processing flow commonly adopted for CISs.

A color image requires at least three color samples at each pixel location. Computer images often use red, green, and blue. To reduce the cost of image sensors, CISs usually use a single sensor covered with a color filter array (CFA) instead of using three separate sensors [6]. The most common CFA structure is the Bayer CFA [7]. By using CFAs, the image produced by the CIS contains only one color component per pixel. Therefore, the first processing is to reproduce the other two missing color components by performing the color demosaic process [8]. The typical color demosaic is based on the bilinear interpolation, where the operation can be regarded as averaging of neighbor pixel values. After the color demosaic process the amount of data to be processed by the following image processes is increased to three times of the original CIS output.

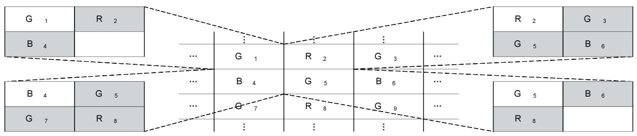

Figure 2. Proposed CIS image signal processing

The purpose of the color correction is to convert the native device color space to a device independent color space. It is implemented by 3D table lookup or by matrix multiplication. In mobile applications which do not require precise color matching, the latter is preferred [9]. The corrected values (R_c, G_c, and B_c) are calculated by multiplying a 3 × 3 color correction matrix (CC) to the interpolated pixel values (R_d, G_d, and B_d), as defined below:

$$\begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} = CC \begin{bmatrix} R_d \\ G_d \\ B_d \end{bmatrix} = \begin{bmatrix} cc_{rr} & cc_{rg} & cc_{rb} \\ cc_{gr} & cc_{gg} & cc_{gb} \\ cc_{br} & cc_{bg} & cc_{bb} \end{bmatrix} \begin{bmatrix} R_d \\ G_d \\ B_d \end{bmatrix}. \quad (1)$$

This matrix multiplication containing six scalar six scalar additions and nine scalar multiplications is the most computationally intensive processing step.

Estimating the color temperature of illuminants and compensating for their effects on the object surface is called white balancing. White balancing scales the values of red and blue components to equalize the overall intensity of color components. The white balance equation is defined as below:

$$\begin{bmatrix} R_w \\ G_w \\ B_w \end{bmatrix} = \begin{bmatrix} wb_r & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & wb_b \end{bmatrix} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix}. \quad (2)$$

The two coefficients wb_r and wb_b are red and blue scale factors computed from auto white balance (AWB) module outside the original image processor.

The gamma correction adjusts color values to make the display intensity on the target display device proportional to the color corrected values [10]. This enables the display devices to reproduce the color intensity that is close to what the eye would perceive.

3 Scaled Color Correction

As the resolution of CISs grows rapidly especially in portable applications, it is desirable to decrease the computational complexity of the CIS image signal processing in order to reduce area and power consumption. Figure 2 shows the proposed image processing procedure in which the color correction block and the white balance block are moved to the front of the color demosaic block.

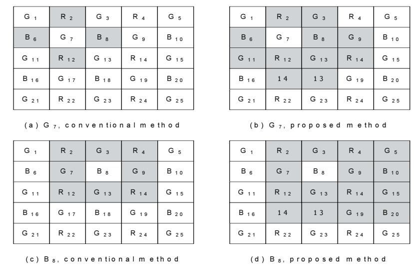

Figure 3. Selection of missing color component from neighbouring pixels

In addition, the two processes are combined into one called the scaled color correction.

As there is only one color component per pixel in the output image obtained from the CIS, it is sufficient to process the color correction on one color component per pixel. Therefore, the color correction equation for a red pixel (R), for example, can be represented as follows:

$$R_c = CC_r \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} cc_{rr} & cc_{rg} & cc_{rb} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3)$$

where CCr is a sub-matrix formed by taking the first row of CC. Each of these matrix multiplications involves two scalar additions and three scalar multiplications per pixel. Note that the computational complexity of Eq. (1) is three times higher than that of Eq. (3).

Since Eq. (3) still requires the values of all three color components (R, G and B) of the pixel, the values of the missing components should be estimated. This process should be simple enough to be negligible in complexity. Otherwise, the proposed method would have no great advantage over the conventional method. Among many ways that have been tried, the following method is introduced here. It is not only simple enough to require a few additional computations but also good in the terms of image quality.

Figure 3 shows the proposed estimation scheme. In this scheme every pixel refers to shaded neighbor pixels on its right, bottom, and right bottom (if needed). The green pixel (G_5) uses the value of the bottom pixel (R_8) as R and the value of the right pixel (B_6) as B. In case of a red pixel (R_2), G is the average of two neighboring green pixels (G_3 and G_5) and B is the value of right bottom pixel (B_6). The set of neighbor pixels used for a blue pixel can be similarly defined. In this case, the color correction equations are defined as follows:

$$R_{2c} = cc_{rr} R_2 + cc_{rg} \frac{G_3 + G_5}{2} + cc_{rb} B_6 \quad (4)$$

$$G_{1c} = cc_{gr} R_2 + cc_{gg} G_1 + cc_{gb} B_4 \quad (5)$$

$$G_{5c} = cc_{gr} R_8 + cc_{gg} G_5 + cc_{gb} B_6 \quad (6)$$

$$B_{4c} = cc_{br} R_8 + cc_{bg} \frac{G_5 + G_7}{2} + cc_{bb} B_4 \,. \quad (7)$$

This scheme requires only a half extra addition to calculate the mean of two green pixels on the average.

Due to its simplicity and linearity white balancing can be easily combined with the color correction operation. Combining Eq. (2) and Eq. (4) to Eq. (7) yields the following scaled color correction equations:

$$R_{2c} = wb_r cc_{rr} R_2 + wb_r cc_{rg} \frac{G_3 + G_5}{2} + wb_r cc_{rb} B_6 \quad (8)$$

$$G_{1c} = cc_{gr} R_2 + cc_{gg} G_1 + cc_{gb} B_4 \quad (9)$$

$$G_{5c} = cc_{gr} R_8 + cc_{gg} G_5 + cc_{gb} B_6 \quad (10)$$

$$B_{4c} = wb_b cc_{br} R_8 + wb_b cc_{bg} \frac{G_5 + G_7}{2} + wb_b cc_{bb} B_4 \,. \quad (11)$$

Note that two constants to be multiplied by a neighbor pixel can be merged into one constant in real implementations. Also note that only one of the above equations is needed for a given pixel position. As a result, the average number of operations needed is three scalar multiplications and two and a half scalar additions.

4 Experimental Results

The proposed image signal processing is modeled and simulated for several practical images. Eight CIS images in which each pixel is represented in 10-bit precision are used as simulation inputs and are dealt with the conventional image processing chain shown in Fig. 1 and the proposed chain shown in Fig. 2 to generate final 8-bit output images. The bilinear interpolation is selected for color demosaic, and sRGB standard gamma function is used for gamma correction. During the image processing, we used fixed point calculation. Table 1 compares the computational complexity needed to process a pixel in the conventional method and the proposed method, where we can see that the computational complexity is reduce to about one third in the proposed method.

The image quality of the proposed method is compared to that of the conventional one in Table 2. The image quality is represented in terms of the peak-signal-to-noise ratio (PSNR). The difference of final images produced by the two methods is not perceptible for all the images we tested. However, the proposed method shows better results than the conventional one, approximately 0.59dB on the average. The higher PSNR performance is mainly related to the fact that in the proposed method more neighbor pixels participate in deciding three color values of a pixel if the color demosaic and color correction are both considered, as shown in Fig. 4.

Method		Addition	Multiplication
Conventional	White Balance	0	2
	Color Correction	6	9
	Total	6	11
Proposed (Scaled color correction)		2.5	3

Table 1. Comparison of computational complexity per pixel

Image	Performance (PSNR, dB)			
	Conventional method			
	Red	Green	Blue	Avg.
Sample 1	32.03	31.52	30.35	31.24
Sample 2	24.55	25.84	23.30	24.44
Sample 3	30.28	32.46	29.24	30.46
Sample 4	30.33	30.93	29.22	30.10
Sample 5	29.83	30.48	27.90	29.26
Sample 6	26.22	29.18	24.68	26.32
Sample 7	32.93	33.63	30.87	32.31
Sample 8	31.33	33.22	29.14	30.91
Average	29.69	30.91	28.09	29.38

Image	Performance (PSNR, dB)			
	Proposed method			
	Red	Green	Blue	Avg.
Sample 1	32.28	31.22	31.20	31.54
Sample 2	25.03	26.14	24.50	25.17
Sample 3	30.71	32.56	30.30	31.08
Sample 4	30.72	30.89	30.13	30.57
Sample 5	30.22	30.60	29.05	29.91
Sample 6	26.61	29.31	25.92	27.05
Sample 7	33.27	33.52	31.81	32.80
Sample 8	31.77	33.10	30.38	31.61
Average	30.08	30.92	29.16	29.97

Table 2. Comparison of PSNR performance

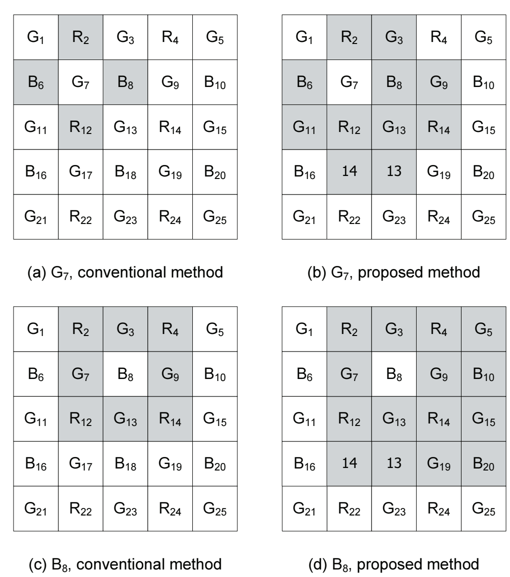

Figure 4. Neighbor pixels affecting three color values of a pixel (G7 and B8) in the final output image

5 Conclusion

A new CIS image signal processing has been presented to reduce computational complexity. Moving the color correction to the front of color demosaic and referencing neighbor pixel values for missing color components reduce the color correction complexity to about one third. The proposed method results in a better PSNR performance compared to the conventional one, although the computational complexity is significantly reduced.

References

[1] A. E. Gamal, "Trends in CMOS image sensor technology and design," in Proc. IEDM, pp. 805-808, Dec. 2002.

[2] A. E. Gamal and Helmy Eltoukhy, "CMOS image sensors," IEEE Circuits and Devices Magazine, vol. 21, pp. 6-20, May 2005.

[3] D. Doswald et al., "A 30-frames/s megapixel real-time CMOS image processor," IEEE J. Solid-State Circuits, vol. 35, pp. 1732-1743, Nov. 2000.

[4] H. Kim, J. -Y. Kim, S. H. Hwang, I. -C. Park, and C. -M. Kyung, "Digital signal processor with efficient RGB interpolation and histogram accumulation," IEEE Trans. Consum. Electron., vol. 44, pp. 1389-1395, Nov. 1998.

[5] Y. H. Jung, J. S. Kim, B. S. Hur, and M. G. Kang, "Design of real-time image enhancement pre-processor for CMOS image sensor," IEEE Trans. Consum. Electron., vol. 46, pp. 184-185, Feb. 2000.

[6] B. K. Gunturk, J. Glotzbach, Y. Altunbasak, R. W. Schafer, and R. M. Mersereau, "Demosaicking: color filter array interpolation," IEEE Signal Processing Magazine, vol. 22, pp.44-54, Jan. 2005.

[7] E. B. Bayer, "Color image array," U.S. Patent 3,971,065, 1976

[8] J. E. Adams Jr., "Interactions between color plane interpolation and other image processing functions in electronic photography," in Proc. SPIE, vol. 2416, pp. 144-151, Feb. 1995.

[9] W. C. Kao et al., "Color reproduction for digital imaging systems," in Proc. ISCAS, pp. 4599-4602, May 2006.

[10] C. A. Poynton, "Gamma and its disguises: The nonlinear mappings of intensity in perception, CRTs, film and video," SMPTE Journal, vol.102, no.12, pp.1099-1108, 1993..