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**Abstract**

This paper presents two algorithms for removing the cross-talk effect in CMOS sensor based color-imaging systems. The algorithms work on the Bayer raw data and have low computational complexity. Experimental results on Macbeth color chart and real images demonstrated that both algorithms can effectively eliminate the cross-talk effect and produce better quality images with conventional color interpolation and correction algorithms designed for CCD image sensors. Complexity of the algorithms is also analyzed.

**Keywords**

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# CMOS SENSOR CROSS-TALK COMPENSATION FOR DIGITAL CAMERAS

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## ABSTRACT

This paper presents two algorithms for removing the cross-talk effect in CMOS sensor based color-imaging systems. The algorithms work on the Bayer raw data and have low computational complexity. Experimental results on Macbeth color chart and real images demonstrated that both algorithms can effectively eliminate the cross-talk effect and produce better quality images with conventional color interpolation and correction algorithms designed for CCD image sensors. Complexity of the algorithms is also analyzed.

## 1. INTRODUCTION

Complementary Metal-Oxide-Semiconductor (CMOS) imaging technology [1,2] is emerging as an alternative solid-state imaging technology to charge coupled device (CCD). This trend can be attributed some of the advantageous properties of CMOS image sensors: low cost (compatible process with standard CMOS technologies), low power consumption, and easy integration with other CMOS signal processing modules. One clear implication of these advantages of CMOS is the possibility of one-chip solution for many applications.

A typical digital color imaging system with one-sensor CMOS imager, as shown in Figure 1, consists of three parts: optical, analogue and digital.

The analogue part is composed of an array of CMOS sensor elements, read-out circuits, amplifiers and analogue-digital (A/D) converters. The color filter array (CFA) in the optical part is used to filter the incident light such that each sensor element is only exposed to one of the primary colors (Red, Green, and Blue) or one of the complementary colors (Cyan, Yellow and Magenta). Figure 2 gives a typical CFA for RGB primary colors.

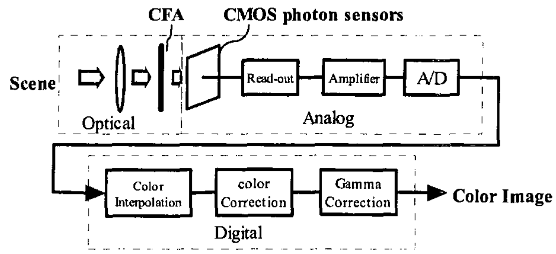


**Figure 1.** A schematic of one-sensor CMOS imaging system

| | | | | | | |
|---|---|---|---|---|---|---|
| G | R | G | R | G | R | G |
| B | G | B | G | B | G | B |
| G | R | G | R | G | R | G |
| B | G | B | G | B | G | B |
| G | R | G | R | G | R | G |
| B | G | B | G | B | G | B |
| G | R | G | R | G | R | G |

**Figure 2.** A typical RGB color filter array

Since the primary/complementary colors are only sparsely sampled, i.e. only one of the color components is sampled at each sensor element, recovery of the missing colors from the sampled ones is necessary in order to generate a color image. This is usually achieved by color interpolation and correction in the digital processing part.

Compared to CCD image sensors, however, CMOS image sensors often perform less satisfactorily due to its unique problems including dark current, fixed-pattern noise (FPN), pixel cross-talk and high random noise. Though recent improvement in CMOS sensor and circuit technology has combated some of the problems [1], cross-talk [3] and random noise [4] remain unsolved.

This paper presents a signal processing based solution to the problem of pixel cross-talk. Section 2 discusses

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in detail the pixel cross-talk and its impact on a finished color image. In Section 3, two algorithms are described for compensating the pixel cross-talk based on our mathematical model [11]. Experimental results on both Macbeth color checker and real images are presented in Section 4. The paper concludes with some remarks in Section 5.

## 2. PIXEL CROSS-TALK

Pixel cross-talk is a phenomenon wherein neighboring pixels interfere with each other [3]. In other words, the response of the sensor at a given pixel depends not only on the incident light at this pixel, but also on its neighbors. It has been observed that the horizontally adjacent pixels interfere with each other much more than vertically adjacent pixels [4] possibly due to the pixel layout.

Considering a CMOS sensor with the RGB CFA as shown in Figure 2, the red pixels interfere with their green neighbors, referred as Gr hereafter, and so do the blue pixels with their green neighbors, referred as Gb hereafter. As a result of the cross-talk, Gr and Gb appear to be different even though they receive the same amount of incident light. Figure 3 shows the light skin color block from Macbeth color checker and the blocky effect caused by the cross-talk. Its average Gr and Gb are 184 and 169 respectively; nearly 10% difference.

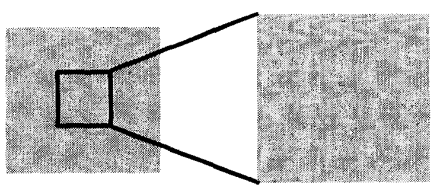

**Figure 3**. Blocky effect on finished color images caused by cross-talk

There are several possible factors that contribute to the cross-talk. Optically, light may pass through one pixel filter at such an oblique angle that it strikes its adjacent pixels by the time it propagates down to the sensor surface. Electrically, sensor read-out circuits may allow for the signal read from one pixel to influence the signal read from another pixel. Architecturally, carriers generated by penetrating photons under a pixel diffuse to a nearby pixel depletion region and are collected by the nearby pixel. The depth to which a photon will penetrate in silicon substrate before generating a carrier is strongly wavelength dependent [7] and the longer the wavelength, the deeper the penetration. Consequently, diffusion would result in a strong cross-talk between red pixels and their neighboring Gr pixels.

In the next section, we present two signal processing based algorithms to combat the cross-talk problem.

## 3. COMPENSATION OF CROSS-TALK

From signal processing perspective, cross-talk can be considered either as random noise or as noise having certain pattern. Application of median filter or its variations [8-10] seems to be a straightforward choice because of its simplicity and effectiveness. However, median filter is good at removing random impulse noise. The fixed pattern characteristic of the cross-talk should be explored as well in order to remove the cross-talk effect effectively.

According to the three hypotheses (physical, electrical and architectural) presented in Section 2 with respect to the sources of cross-talk, it is asserted that the amount of the cross-talk can be estimated locally and its effect can be removed by compensating the difference between the Gr and Gb channel [11]. Using this as a basis, the problem of cross-talk compensation is formulated as follows.

***Cross-talk Compensation***: We estimate the G-channel from the sampled Gr and Gb channels such that the estimation minimizes the error in gradient between the estimated G-channel and the Gr and Gb channels. This estimation criterion maintains the image sharpness. Furthermore, the estimation is subject to either of the following two reasonable assumptions:

1. The local average of the G-channel is confined to either Gr or Gb channel (Algorithm I)
2. The local average of the G-channel is confined to the average of Gr and Gb channel. (Algorithm II)

Notice that the local average can be estimated from the neighborhood of a given pixel.

Without loss of generality, consider the following 5x5 local RGB Bayer raw data (Figure 4), where the central pixel is Gr in (a) and Gb in (b).

With the assumptions above, Algorithm I is based on bilinear interpolation, which adjusts one channel while using the other as a reference, and Algorithm II is based on the local averages of Gr and Gb and modifies both Gr and Gb channels. Both algorithms attempt to minimize the contrast degradation of the color image reconstructed from the Bayer data after the removal of the cross-talk [11].

| | | | | |
|---|---|---|---|---|
| $G_1$ | R | $G_2$ | R | $G_3$ |
| B | $G_4$ | B | $G_5$ | B |
| $G_6$ | R | $G_7$ | R | $G_8$ |
| B | $G_9$ | B | $G_a$ | B |
| $G_b$ | R | $G_c$ | R | $G_d$ |

**(a)**

| | | | | |
|---|---|---|---|---|
| $G_1$ | B | $G_2$ | B | $G_3$ |
| R | $G_4$ | R | $G_5$ | R |
| $G_6$ | B | $G_7$ | B | $G_8$ |
| R | $G_9$ | R | $G_a$ | R |
| $G_b$ | B | $G_c$ | B | $G_d$ |

**(b)**

**Figure 4.** A 5x5 local window from GRBG Bayer pattern. (a) The central pixel $G_7$ is $G_r$; (b) the central pixel $G_7$ is $G_b$

### 3.1 Algorithm I : Interpolation based

In this algorithm, either Gr or Gb is chosen as a reference channel and the other channel will be modified in such a way as to equalize the two channels.

Assuming $G_b$ as the reference, $G_r$ pixel at location 7, as shown in Figure 4(a), shall be modified as

$$G_7^{new} = G_7 + \Delta G_7 \qquad (1)$$

where

$$\begin{aligned} \Delta G_7 &= (\Delta G_4 + \Delta G_5 + \Delta G_9 + \Delta G_a)/4 \\ \Delta G_4 &= G_4 - (G_1 + G_2 + G_6 + G_7)/4 \\ \Delta G_5 &= G_5 - (G_2 + G_3 + G_7 + G_8)/4 \\ \Delta G_9 &= G_9 - (G_6 + G_7 + G_b + G_c)/4 \\ \Delta G_a &= G_a - (G_7 + G_8 + G_c + G_d)/4 \end{aligned}$$

or

$$G_7^{new} = \frac{G_4 + G_5 + G_9 + G_a}{4} + \frac{(8+4)G_7 - [2(G_2 + G_6 + G_8 + G_c) + G_1 + G_3 + G_b + G_d]}{16}$$

Notice that only the green values at $G_r$ pixels need to be adjusted using the method described above if the $G_b$ channel is selected as a reference channel. Similarly, only $G_b$ pixels need to be modified if $G_r$ is the reference.

**Table 1.** Complexity of Algorithm I

| | Number of operations[(1)] |
|---|---|
| Addition/Subtraction | 13*(mn/4) |
| Shift | 10*(mn/4) |
| Multiplication | NILL |
| Division | NILL |
| [(1)] *The estimation is purely based on the formula presented above.* | |

For a *(m x n)*-sized Bayer pattern image, the complexity of the algorithm is shown in Table 1.

### 3.2 Algorithm II – Average based

This algorithm changes both $G_r$ and $G_b$ channels. For a $G_r$ pixel at location 7, as shown in Figure 4(a),

$$\begin{aligned} G_7^{new} &= G_7 + (\overline{G}_b - \overline{G}_r)/2 \\ \overline{G}_b &= (G_4 + G_5 + G_9 + G_a)/4 \\ \overline{G}_r &= (G_1 + G_2 + G_3 + G_6 + G_7 + G_8 + G_b + G_c + G_d)/9 \end{aligned} \qquad (2)$$

For a $G_b$ pixel at location 7, as shown in Figure 4(b),

$$\begin{aligned} G_7^{new} &= G_7 + (\overline{G}_r - \overline{G}_b)/2 \\ \overline{G}_r &= (G_4 + G_5 + G_9 + G_a)/4 \\ \overline{G}_b &= (G_1 + G_2 + G_3 + G_6 + G_7 + G_8 + G_b + G_c + G_d)/9 \end{aligned} \qquad (3)$$

The complexity of the algorithm is shown in Table 2.

**Table 2.** Complexity of Algorithm II

| | Number of operations [(1)] |
|---|---|
| Add/Subtraction | 13*(mn/2) |
| Shift | 3*(mn/2) |
| Multiplication | NILL |
| Division | 1*(mn/2) |
| [(1)] *The estimation is purely based on the formula presented above* | |

### 3.3 Color processing chain with Gr/Gb compensation

Since the proposed algorithms work on the Bayer raw data, it must be placed as the first step in the digital color processing chain, as shown in Figure 5. After the compensation, most existing color interpolation and correction algorithms can be applied even if they have been initially designed for CCD image sensors.

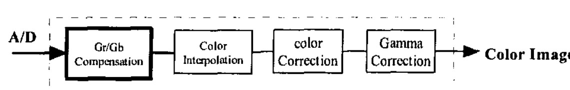


**Figure 5.** Color processing chain with cross-talk compensation

## 4. EXPERIMENTAL RESULTS

Macbeth color checker and real images captured by CMOS image sensor MCM20014 with Bayer-RGB color filter are used for evaluating the performance of the proposed algorithms. MCM20014 is an active VGA CMOS image sensor consisting of square pixel unit cells with pinned photodiode architecture. The pixel pitch is 7.8μm. For color interpolation, we applied an edge-based algorithm as described in [6] together with a color correction with 3x3 matrix.

Table 3 presents the average Gr and Gb values of six color boxes from the Macbeth color checker before and after Gr/Gb compensation using a median filter (M-flt) and the proposed algorithms (Alg I & Alg II). Notice there is about 10% difference between Gr and Gb channel for the same color. The proposed algorithms removed the Gr/Gb difference very well with maximum difference of 1, which is in some cases due to numeric computation error.

**Table 3.** The average Gr and Gb values of 5 color boxes from Macbech color checker before and after Gr/Gb compensation

| Color | | Before | After | | |
|---|---|---|---|---|---|
| | | | M-flt | Alg I | Alg II |
| Skin | Gr | 184 | 169 | 170 | 177 |
| | Gb | 169 | 184 | 169 | 176 |
| Orange | Gr | 151 | 137 | 137 | 144 |
| | Gb | 137 | 151 | 137 | 144 |
| Blue | Gr | 18 | 20 | 20 | 19 |
| | Gb | 20 | 18 | 20 | 19 |
| Green | Gr | 95 | 92 | 92 | 93 |
| | Gb | 92 | 95 | 92 | 93 |
| Red | Gr | 71 | 57 | 58 | 64 |
| | Gb | 57 | 71 | 57 | 64 |
| Grey | Gr | 207 | 199 | 199 | 203 |
| | Gb | 199 | 206 | 199 | 203 |

The median filter operated on every green pixel and its 4 nearest neighbors. However, it just swapped the Gr and Gb channel (column M-flt). This is because at every Gr pixels, there are 4 nearest Gb pixels and every Gb pixel has 4 nearest Gr pixels.

Figure 6, 7, 8 are the finished Macbeth color checker without Gr/Gb compensation and with compensation using Algorithm I and algorithm II respectively. The blocky effect in Figure 6 is usually not noticeable until it's zoomed in. Therefore, a small block of the yellow color was zoomed in by a factor of 3.

Figure 9, 10 and 11 are real images without Gr/Gb compensation and with Gr/Gb compensation using the proposed algorithm I and II respectively. The compensation algorithms do not degrade the sharpness of the images.

## 5. SUMMARY

We proposed two simple and efficient algorithms for removing the cross-talk effect in CMOS image sensor without degrading the sharpness of the images. The algorithms work only on the Green channel of the Bayer raw data. Further improvement on the algorithms might be achieved by taking into consideration the correlation between two the signals: Gr-Gb and R-B.

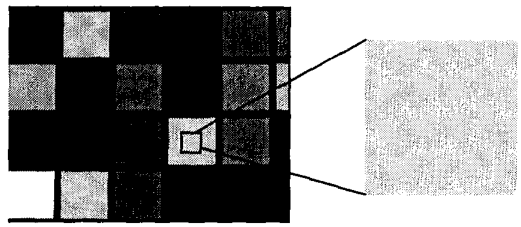

**Figure 6.** Without Gr/Gb compensation

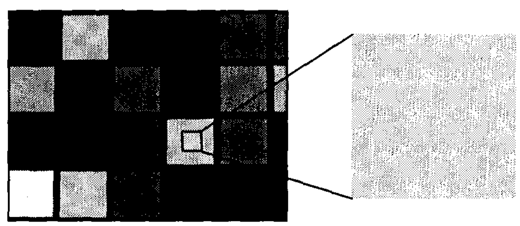

**Figure 7.** Gr/Gb compensation using Algorithm I

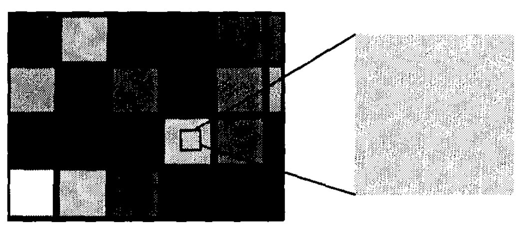

**Figure 8.** Gr/Gb compensation using Algorithm II

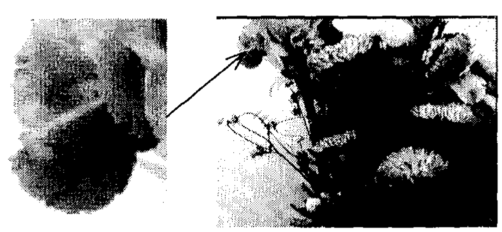

**Figure 9.** Without Gr/Gb compensation

**Figure 10.** Gr/Gb compensation using Algorithm I

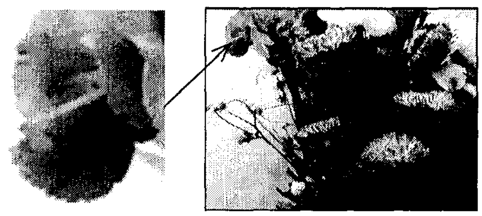

**Figure 11.** Gr/Gb compensation using Algorithm II

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## BIOGRAPHY

**Wanqing Li** received B. Sc. in physics and electronics and M.Sc. in computer science from Zhejiang University, China in 1983 and 1987 respectively. In 1997, he received PhD in electronic engineering from The University of Western Australia, Australia.

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**Yu Shi** received the B.E. degree in electrical engineering from Changsha Polytechnic Institute, Changsha, China, in 1982, and Ph.D degree in bio-medical engineering from National Polytechnic Institute of Toulouse, Toulouse, France, in 1992.

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**Igor Kharitonenko** was born in Odessa, Ukraine. He received his B.S. with honours in electronics engineering and Ph.D. degrees from Odessa Polytechnic University in 1985 and 1993, respectively.

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His research interests include machine vision, CMOS image sensor architectures, image and video compression. Since 1997 he has been involved in ISO activity on JPEG2000 image compression standard development. Dr Kharitonenko holds several patents on digital cameras and digital video communication related technologies.