Crosstalk, color tint and shading correction for small pixel size image sensor

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Abstract

Current trend to reduce pixel size of portable camera modules brings a set of new problems for image sensor designers. The benchmarking shows that most of the portable camera modules are suffering from strong shading and unstable color reproducibility caused by spatial variation of the crosstalk between pixels [1]. This appears as a non uniform color tint on captured images and makes shading profile susceptible to spectral composition of illuminant light. While standard methods based on spatially dependent gain control are sufficiently effective for shading correction (SC) of sensors with large pixel size a more advanced technique is needed to cure crosstalk induced problems of state-of-the-art imager.

The purpose of current study is to construct robust model describing shading, color tinting and crosstalk mechanisms affecting image quality and apply the model for image correction.

The Crosstalk Model

The crosstalk in image sensor is an effect when signal from specific pixel is affected by that of adjacent pixels. The nature of the crosstalk in image sensors has various origins: electron diffusion in photo diode, not sufficient optical separation of pixels or even readout circuit [2,3]. It is natural to assume that image sensor is a linear system, with linear crosstalk existing only between horizontal and vertical neighboring pixels (closest neighbor approximation) and that it is small in comparison with the main signal, Fig. 1. Under this assumption we can use (1) for crosstalk correction:

$$X^* = C_{X,X}\cdot X + C_{L,X}\cdot Left + C_{R,X}\cdot Right + C_{T,X}\cdot Top + C_{B,X}\cdot Bottom \quad (1)$$

In equation (1) asterisk is used for signal in the absence of the crosstalk, we will call it pure or target signal. The constants $C^*_{i,X}$, *i= L,R, T,B* are responsible for crosstalk and $C^*_{X,X}$ is signal gain constant which in general is not unity. If we know parameters $C_{i,X}$, *{i=X, L, R, T, B}*, it is possible to estimate crosstalk-free signal.

R	Gr	R	Gr
Gb	B	Gb	B
R	Gr	R	Gr
Gb	B	Gb	B

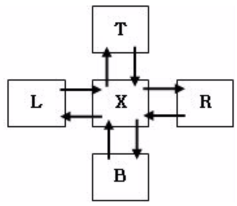

Fig.1 Bayer pattern of color filters and crosstalk interactions between adjacent pixels.

Crosstalk and gain parameters $C_{i,X}$ can be measured experimentally for a given type of the sensor. Unfortunately, it is difficult to distinguish left and right (top and bottom) crosstalk components. So, we may simplify (1) assuming these components are equal.

It is also important to take into account, that crosstalk (and gain) constants are sensitive to spectral composition of light. It is well known [1, 2], that crosstalk for red light is higher than that for blue because of different absorption rate of light in silicon. In case of color image sensor with Bayer color filter pattern we can take this effect into account introducing different crosstalk coefficients for each color channel. Eq. (1) now can be rewritten as:

$$\begin{aligned}
R^* &= C_{R,R}\cdot R + C_{G,R}\cdot\frac{Gr_L+Gr_R+Gb_T+Gb_B}{4}, \text{ for Red pixel}\\
Gr^* &= C_{R,Gr}\cdot\frac{R_L+R_R}{2} + C_{Gr,Gr}\cdot Gr + C_{B,Gr}\cdot\frac{B_T+B_B}{2}, \text{ for Gr pixel}\\
Gb^* &= C_{R,Gb}\cdot\frac{R_T+R_B}{2} + C_{Gb,Gb}\cdot Gr + C_{B,Gb}\cdot\frac{B_L+B_R}{2}, \text{ for Gb pixel}\\
B^* &= C_{G,R}\cdot\frac{Gr_L+Gr_R+Gb_T+Gb_B}{4} + C_{B,B}\cdot B, \text{ for Blue pixel}
\end{aligned} \quad (2)$$

The equation (2) is depending upon 10 different parameters. We have to use one of four equations depending upon the type of pixel to be corrected.

The structure of Eq.(2) is a composition of classical shading correction (CSC), when we apply position dependent signal gain and crosstalk part, which is responsible for signal mixing and is also position dependent. Thus we may refer to the method, based on (2) as a Generalized Shading Correction (GSC)

Eq.2 is the final equation and will be used in the crosstalk correction algorithm.

Crosstalk Parameters Estimation

If we will capture uniformly illuminated image of uniform object (for example white paper) we should expect, that all pixels of resultant image have the same color components (R_0, G_0, B_0). In reality, we may found that the image will have brighter center (effect known as shading), color tinted regions and, probably, regular mosaic due to difference between *Gr* and *Gb* channel sensitivities. Under assumptions made in previous chapter, we can describe these effects in terms of crosstalk model characterized by distribution of 10 coefficients in (2) according to pixel position. In case of uniform object difference between neighboring pixels of the same color channel is negligible and we may simplify equation (2):

$$\begin{bmatrix} R \\ Gr \\ Gb \\ B \end{bmatrix}_{Target} = \begin{bmatrix} C_{R,R} & C_{G,R} & C_{G,R} & 0 \\ C_{R,Gr} & C_{Gr,Gr} & 0 & C_{B,Gr} \\ C_{R,Gb} & 0 & C_{Gb,Gb} & C_{B,Gb} \\ 0 & C_{G,B} & C_{G,B} & C_{B,B} \end{bmatrix} \times \begin{bmatrix} R \\ Gr \\ Gb \\ B \end{bmatrix}_{(i,j)} \quad (3)$$

In this equation *R*, *Gr*, *Gb* and *B* are the components of the Bayer cell containing pixel with coordinates *(i, j)* and target signal is expected value of *R*, *Gr*, *Gb* and *B* if there were no crosstalk. Equation (3) is equivalent to 4 linear-independent equations for 10 variables and can be solved only if we have calibration images captured for $k \geq 3$ different illuminants or colors. In this case equation (3) can be rewritten as an over determined system of linear equations:

$$\begin{bmatrix} R_1 & R_2 & \dots & R_k \\ Gr_1 & Gr_2 & \dots & Gr_k \\ Gb_1 & Gb_2 & \dots & Gb_k \\ B_1 & B_2 & \dots & B_k \end{bmatrix}_{Target} = \begin{bmatrix} C_{R,R} & C_{G,R} & C_{G,R} & 0 \\ C_{R,Gr} & C_{Gr,Gr} & 0 & C_{B,Gr} \\ C_{R,Gb} & 0 & C_{Gb,Gb} & C_{B,Gb} \\ 0 & C_{G,B} & C_{G,B} & C_{B,B} \end{bmatrix} \times \begin{bmatrix} R_1 & R_2 & \dots & R_k \\ Gr_1 & Gr_2 & \dots & Gr_k \\ Gb_1 & Gb_2 & \dots & Gb_k \\ B_1 & B_2 & \dots & B_k \end{bmatrix}_{(i,j)} \quad (4)$$

To complete Eq. (4) we should determine the procedure of evaluation of target signal. To do this in a best way we must understand structure of the sensor and mechanisms of crosstalk.

A typical structure of image sensor is represented on Fig.2. We are assuming that image sensor is made using circuit sharing technology and position dependent microlens and color filter optimization to compensate shading.

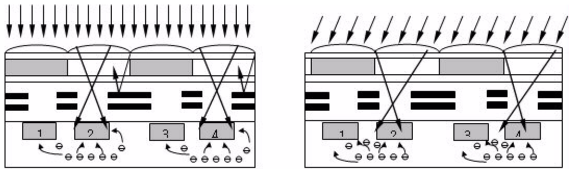

Fig.2 a schematic structure of image sensor and crosstalk behavior at the center (left) and edge (right) region of the image sensor.

A sensor from Fig.2 has several mechanisms of crosstalk. First, electrons generated in depletion region of pixels photodiode can diffuse to the adjacent photodiodes. This effect is known as electrical crosstalk which depends upon the wavelength and incident angle of light. Since it is position dependent it causes non uniform color tinting of captured image. If a circuit sharing technology is applied, adjacent pixel will have different geometry of back-end structure (pixels 1 and 2 on Fig.2). This, in turn, will result in modulation of sensitivity and crosstalk which is the origin of fixed pattern noise. The magnitude of this modulation is also a function of light incident angle and position of the pixel.

A microlens and color filter optimization technology is dedicated to minimize color tinting and shading by adjusting position of microlenses, color filter and metal layers to match specification of camera lens. Normally, at the center of the sensor the photodiode, color filter, microlens and imaging lens are aligned along common optical axis, but this is not true for the edge of the pixels array. It is because of this property, central region has higher sensitivity, best color reproduction and smallest crosstalk.

We may put these considerations into target signal estimation to set

$$\begin{bmatrix} R \\ Gr \\ Gb \\ B \end{bmatrix}_{Target} \equiv \begin{bmatrix} R \\ (Gr+Gb)/2 \\ (Gr+Gb)/2 \\ B \end{bmatrix}_{Center} \quad (5)$$

We intentionally average *Gr* and *Gb* channels to eliminate *Gr/Gb* difference in target signal. Now we may solve (4) for each pixel of the sensor using either pseudo inverse matrix or numerical methods to determine $C_{i,j}$, $i,j=\{R, Gr, Gb, B\}$

Now we may ask what set of images is the best for $C_{i,j}$ estimation. Well, this is closely related to the variation of the object colors and light conditions of scenes to be captured. It may be patches of Gretag Macbeth color checker table or colored paper, but the best results we may achieve by capturing interior of integrating sphere illuminated by monochromatic light. According to our experience, this experimental configuration offers highly uniform images of 'pure' color and possibility to automate the calibration procedure.

Each of 10 elements of matrix in (4) can be characterized by a surface defined on image area. On the basis of analysis of experimentally measured crosstalk parameters distribution, we have decided to approximate it by polynomial function of two variables:

$$S(x,y)=\begin{bmatrix}1 & y & \cdots & y^n\end{bmatrix}\begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1,m+1} \\ s_{21} & s_{22} & \cdots & s_{2,m+1} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n+1,1} & s_{n+1,2} & \cdots & s_{n+1,m+1} \end{bmatrix}\begin{bmatrix}1 \\ x \\ \vdots \\ x^m\end{bmatrix} \quad (6)$$

$$x = i / HorSize,\ 0 \le x \le 1$$
$$y = j / VertSize,\ 0 \le y \le 1$$

In (6) we assume that pixel array resolution is *HorSize* by *VertSize* pixels. According to (6), the crosstalk distribution surface may be described by *(m+1)·(n+1)* constants. In our case we were using m=4 and n=4, so our method requires 250 parameters. We have managed to further reduce number of parameters by zeroing nonsignificant components. We do not present here detailed discussion of this optimization to concentrate our attention on crosstalk related effects.

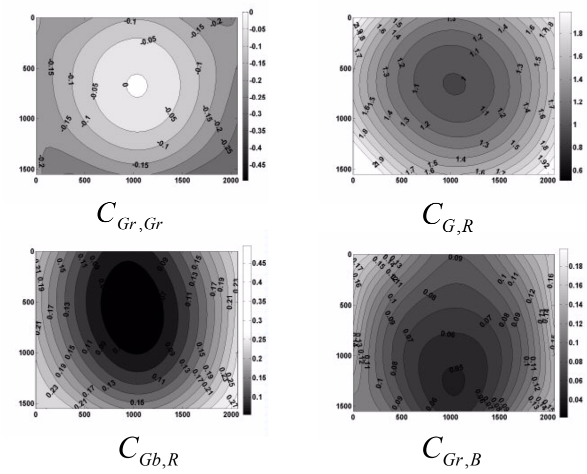

Fig.3 Example of spatial distribution of crosstalk parameters

A spatial distribution of some constants after approximation with (6) is presented on Fig. 3. We may notice that centers of symmetry of the distributions do not coincide with each other. Parameter $C_{Gr,Gr}$ is a diagonal member of matrix in (5) thus responsible for shading correction. A typical magnitude of non-diagonal elements may reach as high as 0.2~0.3 or more than 10% of corresponding diagonal element. This is well noticeable as color tint on captured images if we will keep using the classical shading correction.

The capabilities of the method can be illustrated by means of spectral response (Fig.4). These graphs show relative sensitivity to a monochromatic light for each color channel in selected region of pixel array. In case when sensor operates in linear regime, spectral response provides us full information about color reproduction.

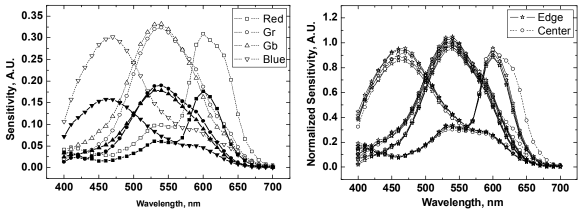

Fig.4 Spectral response and sensitivity comparison for preprocessed images. On the left graph sensitivity comparison between center (dashed line) and bottom right corner (solid line) is shown. On the right graph data from all 4 corners and the center of the sensor is normalized to the maximum of (Gr+Gb)/2 to show spectral response variation.

On Fig.4 spectral responses of central and edge regions of image sensor are compared. We may see that sensitivity of the central region is much higher than that of the edge. Even if we will apply normalization, difference between *Gr* and *Gb* channels as well as variation of spectral responses (Fig.4, Right) will remain. We may notice a strong difference between center and edge for red color channel response. This discrepancy occurs due to infrared (IR) cut-off filter. In our camera modules we are using interference-type IR filter so cut-off wavelength depends upon light incident angle.

We measure spectral response by capturing interior of integrating sphere illuminated by monochromatic light (400 to 700nm). Extracted from the images color channel signals are normalized to optical power and presented as a graph. If we apply our correction algorithm for these 'raw' images, we may easily observe how the method works. There is almost no difference in sensitivity between the center and edge (Fig.5, Left), negligibly small spectral response variation (except region, affected by IR filter) and no difference between *Gr* and *Gb* (fig.5, Right). This is another reason to refer our method to as Generalized Shading Correction. Unlike classical shading correction when we equalize 'integral' sensitivity GSC equalizes spectral response.

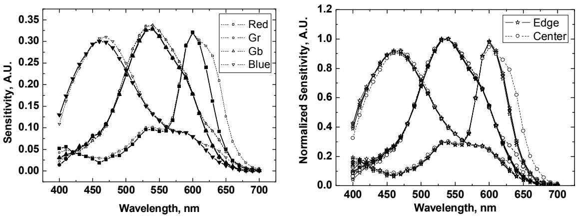

Fig.5 Spectral response and sensitivity comparison for preprocessed images. Figure layout is similar to Fig.4.

Results and Discussion

As we have shown, GSC method is capable to equalize color response of the sensor and compensate crosstalk-induced difference between Gr and Gb channels. Unlike the existing adaptive methods, where parameters for image filtering are estimated during capturing process [4], we are performing calibration based correction. This is very important property because it may correct many of image defects caused by sensor's structure with minimal losses of visual information like resolution and SNR.

First of all, we are able to correct crosstalk occurring when there is mismatch between microlens shift and imaging lens specification. In addition, we may cure modulation of sensitivity of Gr and Gb channels resulting from different pixel geometry (Fig.2).

Another important application is a camera module with optical zoom. In this case it is impossible to perform a microlens optimization for all possible zooms. If we will not use information about crosstalk distribution for a specific zoom for image enhancement, there will be strong image quality degradation. GSC method is one of the possible solutions.

Besides sensitivity equalization, the method enables us to improve color reproduction uniformity. This is one of the most common defects of existing portable camera. If fabrication process stability is good enough to provide no sample variation of color reproducibility, we are able to equalize color response with much more flexible image processing technique rather than fine-tuning of the sensors structure.

In conclusion, we are presenting comparison of our method and CSC on fig 6 and 7. Both methods were using the same test images for calibration (i.e. images taken upon illumination by monochromatic light and white target illuminated by fluorescent lamp which is different from scene illuminant, a halogen lamp) and were applied to the same images. An image interpolation and white balance were applied to the data after Classical / Generalized shading correction.

On fig.6 we are comparing overall uniformity of color reproduction of the sensor. This effect is a result of spectral response variation, presented on Fig.4 and 5. A fine detail image is shown on Fig.7. We may clearly see a checker board like noise that is pronounced on finger and almost absent on white keyboard.

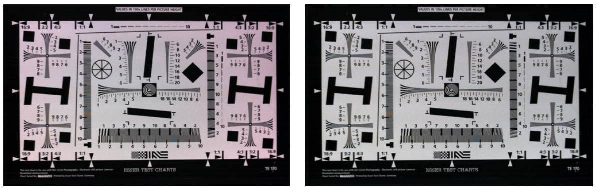

Fig.6 is an illustration of color tint correction. An image processed with CSC method is shown on left while image obtained with GSC is shown on right.

Fig.7 is an illustration of pattern noise correction. An image processed with CSC method is shown on left while image obtained with GSC is shown on right.

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