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Gain and Offset Fixed Pattern Noise Correction Method in CCD Sensors

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Abstract

The method that is presented in this paper uses a column shifting technique to correct the fixed pattern noise (FPN) in an image sensor. FPN is An important parameter in imaging devices such as CCD or CMOS. CCD and CMOS sensors have widespread applications, such as star trackers, visible and IR imaging devices. Therefore the precision improvement is an important factor in their performance. There is no simple technique to remove FPN without any inconvenience. The proposed algorithm can reduce both, gain and offset of FPN noise. At first the gain FPN of all pixels will be unified. Then, the same procedure applies to the offset FPN. This unification is applied using two shifted images from the scene. Comparing other methods which need thousands of frames to reduce FPN noise, this technique is more efficient and much faster. The efficiency of proposed algorithm has been proved by simulation results. The proposed algorithm is applied to satellite and star tracker sample images. This technique also can be used in any camera or infrared devices that use focal arrays system to observe the scenes.

Keywords: CCD; CMOS; fixed pattern noise; satellite; sensors; star tracker;

INTRODUCTION

FPN or non-uniformity is the spatial deviation in output pixel values under constant illumination because of device mismatches and process parameter variations through an image sensor. It is a significant source of image quality degradation especially in CMOS image sensors [1, 2]. After launching the first satellite (Sputnik 1), thousands of them have been launched into orbit around the earth. The commonly used altitude classifications are low earth orbit (LEO), medium earth orbit (MEO) and high earth orbit (HEO). Low earth orbit is below 2000 km. satellite orbits depend on properties and objectives of sensors, they carry. For instance most of remote sensing satellites are placed in near-polar orbits.

Recently high attitude accuracy has become more important. Attitude determination process determines the orientation of satellite with respect to a reference frame. Most Satellites use a star tracker to determine their attitude. Star tracker is an electronic camera that is connected to a processor [3]. They are classified based on different imager technologies such as active pixel sensor (APS), charge coupled device (CCD) or charge injection device (CID). Most commercial star trackers use CCD chips, because the CCD chips are low noise and are easily available. In recent decades, the use of LEO satellites has increased with the huge development of space technology. Commercial star trackers usually have mass of 3kg, accuracy of 10” (pitch/yaw) and 40” (roll), update rate of 40Hz and power consumption of 10W. Power consumption and radiation effects and mass can be reduced using APS systems. Evolution of CMOS sensors, also called APS, represent a new era in the idea of star trackers. APS based system provides advantages, such as high radiation tolerance, random access capability, advanced capacity of integration in a system and standard CMOS clocking voltage. Although these devices are not as developed as CCDs [4]. These mentioned sensors suffer from variety of noises and other disadvantages. Fixed pattern noise is one of these disadvantages. FPN refers to, pixel to pixel variation [5, 6]. It is mainly due to dark current differences and it is fixed for a specific sensor, but change from sensor to sensor. FPN includes gain and offset component that is random in CCD image sensors. CMOS sensors due to their readout circuit suffer from column FPN that appear as strip bands in the image [7].

There are some methods for reducing FPN, such as correlated double sampling and flat fielding techniques [8]. These methods have many drawbacks, for example FPN noise changes with temperature and time. Since those methods reducing the FPN with permanent data, after some time periods or with temperature variation, may not work correctly. A star tracker uses camera in order to determine satellite attitude, therefore such methods can’t be used because they are forced to interrupt the camera imaging for calibration and many of them need laser and laboratorial devices. So we need to reduce the FPN without interruption and also need such process that can be upgraded during the time. Some methods also need thousands of frames for FPN reduction. Mentioned sensors need a black body to reduce nonlinearity or offset FPN which is expensive and need specific mechanical hardware and interruption of camera. Thus nowadays those techniques which are based on post processing have become more important [9]. In this paper a method is proposed, that reduces both, the gain and offset FPN in CCD sensors. This technique also can be used in any focal array imaging devices that follow linearity response model such as infrared focal arrays. It just needs a few frames to reduce both gain and offset FPN noise, significantly. The proposed algorithm uses integer or non-integer shifting to acquire more information about pixels and FPN parameters.

The rest of this paper is as follow:

In next section the sensor model has been explained. In section III different parts of the proposed algorithm have been described. The simulation results and conclusion have been displayed in sections IV and V.

FPN and Sensor Model

Fixed pattern noise includes gain and offset values. In CCD sensors because of unique amplifier for all pixels we have random FPN. However, in CMOS due to its perpendicular readout system, FPN appears in vertical line. Common linear model for each pixel is used. For specific pixel the output is come in below:

$$y = ax + b \tag{1}$$

where, "*y*" is output signal of CCD for this pixel, "*a*" is gain FPN, "*b*" is offset FPN and "*x*" is input illumination that this pixel has been received. For ideal pixel without FPN noise, the value of "*b*" is zero and "*a*" must be equal to one. In a real image only the magnitude of "*y*" is calculable and the other parameters ("*a*", "*b*", "*x*") are unknown. If the complete arrays detector needs to be modeled, there are M×N pixels. Each pixel treats as a line, which has a different gain and offset value. Each pixel has its own model that produce nonuniformity in the detector and each of them has a unique output versus its illumination. After applying proposed algorithm that will be described at incoming sections, the whole pixels treat as a unique line. The output also can be written as following equation:

$$y_i(m,n)=a(m,n)x_i(m,n)+b(m,n) \tag{2}$$

In this equation $y_i(m,n)$ represents the output of the pixel located in the m'th row and n'th column at i'th frame. In some methods, the value of $a(m,n)$ considered to be unite, or $b(m,n)$ considered to be zero, then FPN will be corrected. But we keep gain and offset values and then correct both of them.

Algorithm Description

Basic and Conditions

This algorithm is based on three images that are taken in a quick interval. These images can be provided, as satellite moves and takes images for procedure of star tracking. Hence, there are relations between pixels information. We can exploit these features and alter parameters of output pixels and improve these images. The second image is shifted version of the first image and third image is the shifted version of the second or first image. As much as more pictures are taken, the more information can be obtained, but these three images are sufficient to provide the information for the proposed algorithm. The detector that we considered is like Fig. 1. The detector is under illumination. Yellow arrows display input illumination and blue arrows represent output signal of detector.

Gain Unification in Adjacent Pixels

Suppose that a 4×4 elements linear arrays CCD is considered, hence, for the first column of detector that is displayed in Fig.1, we can write:

$$\begin{aligned} y_1(1,1) &= a(1,1)x(1,1)+b(1,1) \\ y_1(2,1) &= a(2,1)x(2,1)+b(2,1) \\ y_1(3,1) &= a(3,1)x(3,1)+b(3,1) \\ y_1(4,1) &= a(4,1)x(4,1)+b(4,1) \end{aligned} \tag{3}$$

where "y" represents the output signal of the detector. As was mentioned, only this value has been acquired and the rest are still unknown. In the next frame we have:

$$\begin{aligned} y_2(1,1) &= a(1,1)x(2,1)+b(1,1) \\ y_2(2,1) &= a(2,1)x(3,1)+b(2,1) \\ y_2(3,1) &= a(3,1)x(4,1)+b(3,1) \end{aligned} \tag{4}$$

As it is seen there is a relationship between these equations and the first frame equations. According to short time interval between capturing images, we suppose that the illumination of scene is constant in these frames. Fig 2 displays shifted detector for one pixel shifting that makes second frame equations. Second pixel shifting is performed to allow us have following equations.

$$\begin{aligned} y_3(1,1) &= a(1,1)x(3,1)+b(1,1) \\ y_3(2,1) &= a(2,1)x(4,1)+b(2,1) \end{aligned} \tag{5}$$

The condition in (4) is like (3), only the difference is one pixel shifting in arrays. Fig. 2 shows this movement. In (5), there is two times shifting instead of one time shifting that is explained. In second frame, information of the last equation and in third frame, information of two first equations will be lost.

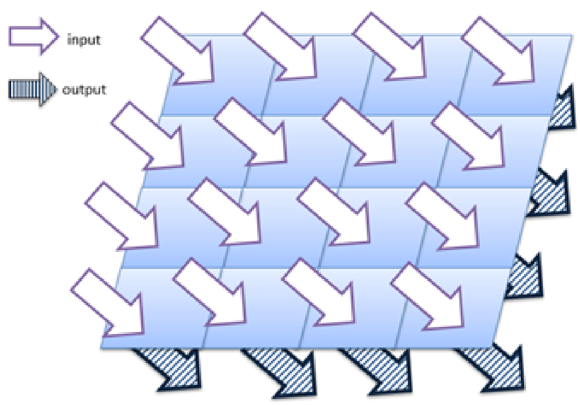

Fig.1. Detector arrays exposure

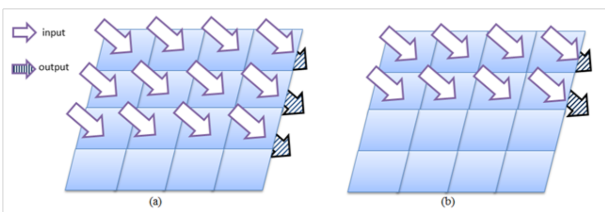

Fig.2. (a) Detector arrays exposure with one pixel shifting (second frame) and (b) two pixel shifting

This information distortion causes that *a(4,1)* element could not unified simply. But this problem will be solved at next sections. The gain unification can be performed by applying these equations.

$$y_3(1,1)-y_2(1,1)=a(1,1)\big(x(3,1)-x(2,1)\big) \quad (6)$$
$$y_2(2,1)-y_1(2,1)=a(2,1)\big(x(3,1)-x(2,1)\big)$$

By dividing these two equations we have:

$$\frac{a(1,1)}{a(2,1)}=\frac{y_3(1,1)-y_2(1,1)}{y_2(2,1)-y_1(2,1)}=f_1(2,1) \quad (7)$$
$$\frac{a(1,1)}{a(3,1)}=\frac{y_3(2,1)-y_2(2,1)}{y_2(3,1)-y_1(3,1)}\times\frac{y_3(1,1)-y_2(1,1)}{y_2(2,1)-y_1(2,1)}=f_1(3,1)$$

In (7), $f_1(3,1)$ obtained in same way as $f_1(2,1)$. $f_1(3.1)$ is called unification factor of pixel 2, with first pixel in first column. Because of information distortion that discussed before, $f_1(4,1)$ cannot be calculated yet.

After applying $f_1(2,1)$ and $f_1(3,1)$ to first frame equations, it is seen that the gain of all pixels, except last pixel can be unified.

$$y(1,1)=a(1,1)x(1,1)+b(1,1)$$
$$y(2,1)\times f_1(2,1)=a(1,1)x(2,1)+b(2,1)\times f_1(2,1) \quad (8)$$
$$y(3,1)\times f_1(3,1)=a(1,1)x(3,1)+b(3,1)\times f_1(3,1)$$
$$y(4,1)=a(4,1)x(4,1)+b(4,1)$$

Last Column Unification Factor Determination

Since we have not shift information about last column pixel, we have to estimate the last unification factor with extra relations.

$$y_2(3,1)=a(3,1)x(4,1)+b(3,1) \quad (9)$$

Therefore *x (4,1)* can be written as:

$$x(4,1)=\frac{y_2(3,1)-b(3,1)}{a(3,1)} \quad (10)$$

Applying (10) in $y_1(4,1)$ we have:

$$y(4,1)=a(4,1)x(4,1)+b(4,1)$$
$$y(4,1)=a(4,1)\left(\frac{y_2(3,1)-b(3,1)}{a(3,1)}\right)+b(4,1) \quad (11)$$
$$y(4,1)=\frac{a(4,1)}{a(3,1)}y_2(3,1)+\left(b(4,1)-b(3,1)\frac{a(4,1)}{a(3,1)}\right)$$
$$\cong\frac{a(4,1)}{a(3,1)}y_2(3,1),$$
$$\frac{a(4,1)}{a(3,1)}\cong\frac{y(1,4)}{y_2(3,1)}$$

In (11) value of *y(4,1)* is approximated, because the value of $b(4,1)-b(3,1)\frac{a(4,1)}{a(3,1)}$ is negligible. Therefore the value of $f_1(4,1)$ could be estimated as:

$$f_1(4,1)=\frac{a(1,1)}{a(4,1)}=\frac{a(3,1)}{a(4,1)}\times\frac{a(1,1)}{a(3,1)}=\frac{y_2(3,1)}{y(4,1)}\times f_1(3,1) \quad (12)$$

The gain unification can be rewritten as:

$$y(1,1)=a(1,1)x(1,1)+b(1,1)$$
$$y(2,1)\times f_1(2,1)=a(1,1)x(2,1)+b(2,1)\times f_1(2,1) \quad (13)$$
$$y(3,1)\times f_1(3,1)=a(1,1)x(3,1)+b(3,1)\times f_1(3,1)$$
$$y(4,1)\times f_1(4,1)=a(1,1)x(4,1)+b(4,1)\times f_1(4,1)$$

Hence, so far, the gain FPN has been unified. Then offset FPN must be unified. The final equation for gain correction can be written as following:

$$Y(m,n)=y(m,n)\times f_m(m,1) \quad (14)$$

where $Y(m,n)$ is corrected output and $f_m(m,1)$ can be obtained as:

$$\frac{y_3(m,n-1)-y_2(m,n-1)}{y_2(m,n)-y_1(m,n)}\times f_m(m-1,1)=f_m(m,1) \quad (15)$$

Offset Unification in Adjacent Pixels

From (13) and (14) we have:

$$Y_1(1,1)=a(1,1)x(1,1)+b(1,1)\times f_1(1,1) \quad (16)$$
$$Y_1(2,1)=a(1,1)x(2,1)+b(2,1)\times f_1(2,1)$$
$$Y_1(3,1)=a(1,1)x(3,1)+b(3,1)\times f_1(3,1)$$
$$Y_1(4,1)=a(1,1)x(4,1)+b(4,1)\times f_1(4,1)$$

where $f_1(1,1)=1$, the second and third frame equations, which is shown in Fig. 2(b), change to these:

$$Y_2(1,1)=a(1,1)x(2,1)+b(1,1)\times f_1(1,1) \quad (17)$$
$$Y_2(2,1)=a(1,1)x(3,1)+b(2,1)\times f_1(2,1)$$
$$Y_2(3,1)=a(1,1)x(4,1)+b(3,1)\times f_1(3,1)$$

and

$$Y_3(1,1)=a(1,1)x(3,1)+b(1,1)\times f_1(1,1) \quad (18)$$
$$Y_3(2,1)=a(1,1)x(4,1)+b(2,1)\times f_1(2,1)$$

Offset unification constant can be defined for bias values, like gain unification factor. These constants could be obtained from (16) and (17).

$$b(1,1)\times f_1(1,1)-b(2,1)\times f_1(2,1)$$
$$=Y_2(1,1)-Y_1(2,1)=B_1(2,1),$$

$$b(1,1)\times f_1(1,1)-b(3,1)\times f_1(3,1) \quad (19)$$
$$=Y_2(2,1)-Y_1(3,1)+B_1(2,1)=B_1(3,1),$$

$$b(1,1)\times f_1(1,1)-b(4,1)\times f_1(3,1)$$
$$=Y_2(3,1)-Y_1(4,1)+B_1(3,1)=B_1(4,1)$$

After adding *B* values to the main equation, detectors output could be unified such that it completely treats linear.

$$\begin{aligned} Y_1(1,1)+B_1(1,1)&=a(1,1)x(1,1)+b(1,1)\times f_1(1,1)\\ Y_1(2,1)+B_1(2,1)&=a(1,1)x(2,1)+b(1,1)\times f_1(1,1)\\ Y_1(3,1)+B_1(3,1)&=a(1,1)x(3,1)+b(1,1)\times f_1(1,1)\\ Y_1(4,1)+B_1(4,1)&=a(1,1)x(4,1)+b(1,1)\times f_1(1,1)\end{aligned} \quad (20)$$

where $B(1,1) = 0$. This equation can be extended to all pixels with following equation.

$$B_m(m,1)=Y_2(m-1,1)-Y_1(m,1)+B_m(m-1,1) \quad (21)$$

The final correction formula can be calculated as:

$$\zeta(m,n)=y(m,n)\times f_m(m,i)+B_m(m,i) \quad (22)$$

Non Integer Shifting

Integer shifting is explained in previous sections. It is very probable that, there is non-integer shifting in an image, because it is not simple to shift the image exactly as long as pixels size. Suppose that the image is shifted vertically with α, between two frames. Below image shows non integer shifting between first and second image. For the first frame we can write following equations same as integer equations:

$$\begin{aligned} y_1(1,1)&=a(1,1)x(1,1)+b(1,1)\\ y_1(2,1)&=a(2,1)x(2,1)+b(2,1)\\ y_1(3,1)&=a(3,1)x(3,1)+b(3,1)\\ y_1(4,1)&=a(4,1)x(4,1)+b(4,1)\end{aligned} \quad (23)$$

For second frame (Fig. 3(a)) and first column, equations will be changed to below:

$$\begin{aligned} y_2(1,1)&=a(1,1)[(1-\alpha)x(1,1)+\alpha x(1,2)]+b(1,1)\\ y_2(2,1)&=a(2,1)[(1-\alpha)x(2,1)+\alpha x(3,1)]+b(2,1)\\ y_2(3,1)&=a(3,1)[(1-\alpha)x(3,1)+\alpha x(4,1)]+b(3,1)\\ y_2(4,1)&=a(4,1)[(1-\alpha)x(4,1)]+b(4,1)\end{aligned} \quad (24)$$

In third frame, the sensor is shifted vertically with α in opposite direction of first frame. Fig. 3(b) shows the third frame with non-integer shifting. For this frame we can write:

$$\begin{aligned} y_3(1,1)&=a(1,1)(1-\alpha)x(1,1)+b(1,1)\\ y_3(2,1)&=a(2,1)[\alpha x(1,1)+(1-\alpha)x(2,1)]+b(2,1)\\ y_3(3,1)&=a(3,1)[\alpha x(2,1)+(1-\alpha)x(3,1)]+b(3,1)\\ y_3(4,1)&=a(4,1)[\alpha x(3,1)+(1-\alpha)x(4,1)]+b(4,1)\end{aligned} \quad (25)$$

$$\begin{aligned} y_3(2,1)-y_1(2,1)&=a(2,1)\alpha[x(1,1)-x(2,1)]\\ y_1(2,1)-y_2(2,1)&=a(1,1)\alpha[x(1,1)-x(2,1)]\end{aligned} \quad (26)$$

Then the gain unification factor of non-integer shifting could be extracted as:

$$f(2,1)=\frac{a(1,1)}{a(2,1)}=(\frac{y_3(2,1)-y_1(2,1)}{y_1(2,1)-y_2(2,1)}) \quad (27)$$

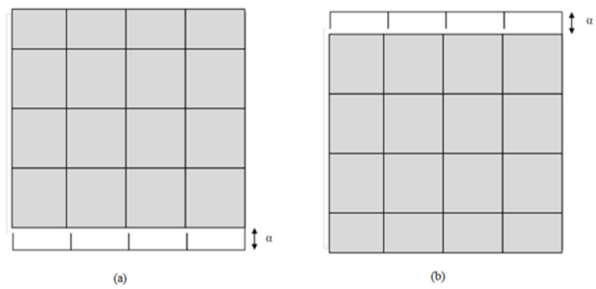

Fig.3. (a) Non integer shifting in second frame. (b) Non-integer shifting in third frame

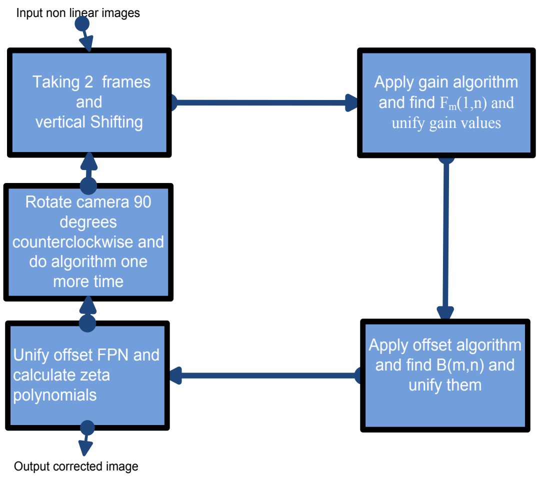

Fig.4. Description of proposed algorithm

Important aspect of proposed technique is that, there is no need to know the value of α . The other unification factors of gain and bias also can be obtained in the same way. The third frame shifting technique is changed to eliminate the value of α in the equations.

One column could be unified until now. 90 degrees rotation of the camera can help us to find the relation between columns. It means that the camera rotates 90 degrees and then the proposed algorithm applied to image again, one more time. After unifying the first column, the remaining columns and all of pixels can be unified. Procedure of proposed algorithm is explained in Fig. 4. The algorithm initially unifies the first column. Then, the camera rotates and this process will be continued again until all of pixels will be unified. The ideal offset could be easily obtained by comparing offset values. For example in (19) every pixel bias values compared with first pixel. It could be extended to find out the best bias value. In order to find the best gain value, the same procedure is conducted. Hence, the unification will be based on the best gain and bias values rather than first pixel.

SIMULATION RESULTS

For testing the proposed algorithm, firstly we simulate a detector that follows the linear model which described earlier. For each photo, after and before applying algorithm, the mean squared error (MSE) is computed. MSE calculates the average of the squares of the errors. Figure 5 shows an image that is taken by 12 Megapixels Panasonic LUMIX DMC-GF3 with the 14mm lens camera. The original image has negligible FPN noise. 5% gain FPN and 10% bias FPN noise added to the raw

Fig.5. Correction with 5% gain and 10% bias FPN noise. (left) Before correction whit MSE = 33.88. (right) After correction with MSE = 4.95.

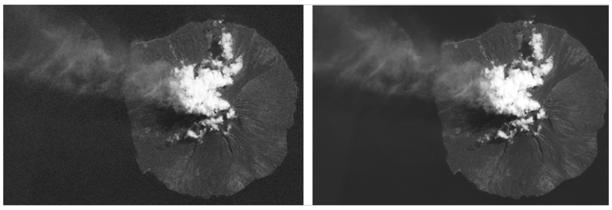

Fig.6. Satellite image with 5% gain and 10% bias FPN noise (left) Before correction whit MSE = 34.38 (right) After correction with MSE = 1.49

image randomly. After adding FPN noise to the image, the proposed algorithm applied to it. This image is shown in Fig. 6, after and before adding noise. The MSE is reduced from 33.88 to 4.95 for pictures in Fig. 5. In practice the algorithm need three integer or non-integer shifted frame, but in our simulation the camera shifting process was simulated. This means that, when the FPN noise is modeled to image, it is possible to shift the image which is similar to practical shifting. Suppose that, first rows of detector should be replaced second row and then, each parameter of gain or offset noise in this row, apply to new pixels that are shifted. It is possible to simply, changes the algorithm in non-integer shifting process as described before. After obtaining unification constants and coefficients, these parameters could be used in the other pictures. If satellite images could be modeled in a linear manner, the proposed FPN reduction technique would be applied to the pictures once in a few weeks.

The proposed algorithm also has been applied to a real satellite image. Part of this image before and after applying algorithm has been shown in Fig 6. This image is taken by NASA's Earth Observing-1 (EO-1) satellite from a volcano.

CONCLUSION

In the star tracker the light distribution of stars is very important and if it is defected by noises, such as FPN and nonlinearity, the exact center of stars could be dislocated. In this paper, an algorithm is proposed which is based on pixel shifting. The algorithm could be extended easily to non-integer pixel shifting mode. The proposed algorithm has been described with an example of 4×4 detector for simplification. It is seen that this procedure reduced nonlinearity of FPN of a typical stars image and improved image quality. All pixels have been unified with gain factors and offset constants. Also it is possible to write an algorithm to find the best pixel in the detector which has ideal gain factor and minimum offset value and then, unify all pixels with its characteristics. However this algorithm cannot completely fix both, gain and offset, but it unifies them in a simple way. Algorithm also has been applied to a real satellite image and as it is seen the FPN noise that added to the raw image had been reduced. For example in satellite images, the MSE is reduced from 34.38 to 1.49 in 15% total FPN noise.

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