Noise Power Spectrum Estimation of Column Fixed Pattern Noise in CMOS Image Sensors Based on AR Model

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***Abstract*—CMOS image sensors are extensively utilized in digital imaging systems for their excellent performance and low power consumption. As an essential components in the system, CMOS image sensors are expected with low noise levels. The images captured by CMOS image sensor contain random noise (RN), digital noise (DN), and fixed pattern noise (FPN). FPN of CMOS image sensors has a greater impact on the perceived image quality than random noise, which seriously restricts the development and application of CMOS image sensors. This paper proposed a noise power spectrum (NPS) method for estimating column FPN of CMOS image sensor based on AR model. First, dozens of images under uniform illumination are acquired by established test vehicle. Second, random noise of the images is restrained by using the multi-frame averaging method. Then, column FPN is modeled by an autoregressive (AR) random process subsequently. Ultimately, column FPN is estimated by calculating NPS of the image based on the AR model. A case application was proposed by using this method.**

Keywords—CMOS image sensor; noise power spectrum; column FPN; AR model; noise; images

I. Introduction

With the technology of the modern semiconductor and integrated circuit developing rapidly, the image quality, illumination sensitivity and resolution of complementary metal oxide semiconductor (CMOS) image sensors is constantly increasing. CMOS image sensors gradually become the mainstream product to acquire images in the world [1]. Because two-dimensional noises are contained in images captured by the CMOS image sensor, the image quality is restrained.

These two-dimensional noises contain RN, DN, and FPN. FPN is an inherent noise caused by different pixel characteristics and is not affected by time [2]. FPN becomes the main noise type that restricts and affects the development and application of CMOS image sensor, because the visual impact of FPN is 5 times than other noises in the same magnitude, and FPN is easier to be observed [3].

Standard deviation (SD) or NPS method is usually used to evaluate noise [4]. The SD method uses a simple way to calculate noise level, but in some cases, such as image reconstruction which using collected data to construct images or simulated noise, it will obtain a inaccurate result [5]. The NPS method can describe the noise frequency variation of reconstructed images, but with the low noise level of FPN, NPS method limited by large variance and low resolution, which often leads to the submergence of weak signals and the appearance of false peaks [6].

In this paper, a noise power spectrum method based on AR model (AR-NPS) was proposed. We built a test vehicle for CMOS image sensor to capture images. Using AR-NPS method to estimate the column FPN, which was extracted by multi-frame averaging method.

This paper is organized as follow: section II introduce the component of test vehicle for CMOS image sensor. The specific test flow for COMS image sensor to capture images is described in section III. The column FPN of CMOS image sensor is estimated by NPS method based on AR model in section IV, and the conclusion is given in section V.

II. Test Vehicle

The test vehicle for CMOS image sensor is composed of a uniform light field generation system and an imaging system. The uniform light field generation system generates uniform light and illuminate it on CMOS image sensor. The imaging system drives the CMOS image sensor to capture images and import them into the evaluation system.

The uniform light field generation system is showed in Fig. 1. It consists of a power supply module, an adjustable light source part, an integrating sphere, optical power meter, and a darkroom with an electronically controlled lifting platform. Among these device, the power module provides a stable voltage for the system to ensure the stability of the brightness of the light source, the integrating sphere is used to produce a highly uniform light field, the darkroom can isolate the interference of natural light in the external environment, the optical power meter is used to measure the uniformity of the light field, the electronically controlled lifting platform is used to place CMOS image sensor and change the position of the sensor.

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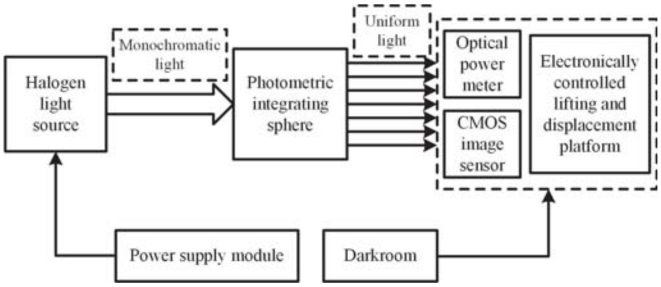

Figure 1. The structure of uniform light field generation system.

The imaging system consists of two parts: a host computer drives the CMOS image sensor to collect image data; a slave computer sets parameters such as exposure time, gain value, and the number of captured images. It mainly includes some modules: AD converter can convert analog signal acquired from CMOS image sensor into digital signal; FPGA processing module is used to transfer image data between slave computer and host computer; Image acquisition card can store images captured by CMOS image sensor. The structure of imaging system is shown in Fig. 2.

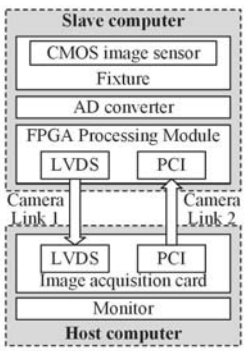

Figure 2. The structure of imaging system.

According to the structure of uniform light field generation system and imaging system. We built a specific test vehicle for the estimation of column FPN which is shown in Fig. 3.

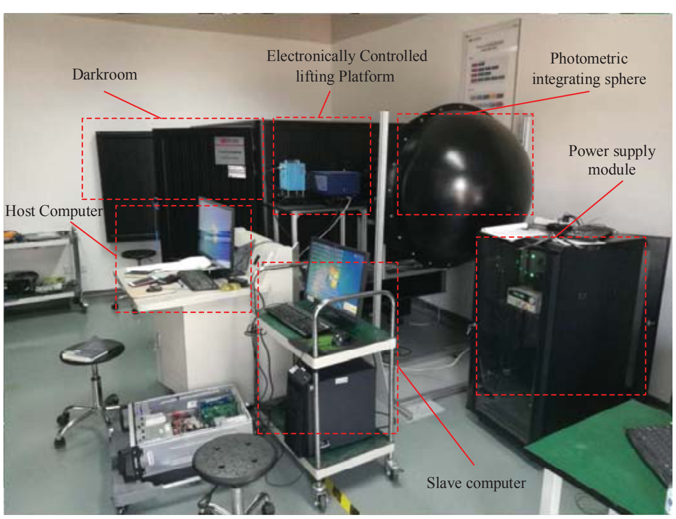

Figure 3. The specific test vehicle.

III. ACQUISITION OF IMAGESZ

In this paper, we used a specific CMOS image sensor to capture images by using the established test vehicle, and estimated its column FPN. The CMOS image sensor has 2048×2048 pixels and its feature is shown in Fig. 4. We carried out some tests according to the EMVA Standard 1288, which contain: the distance between CMOS image sensor and central outlet of photometric integrating sphere should be eight times than the diameter of photometric integrating sphere, in order to ensure each pixel of CMOS image sensor can be irradiated by uniform light; the uniformity of uniform light is required to more than 99%; the average gray value of the captured images is required to be 50% of the saturation value for column FPN estimation [7]. The test flow of CMOS image sensor is summarized in Fig. 5, which is summarized as follows:

- Step 1: Set the gain to the minimum on the premise that the gray value of CMOS image sensor can reach the saturation by adjusting the luminance of uniform light. Then, regulate the luminance of the light, so that the exposure time of 50% exposure is between 10 and 50 (ms). In order to ensure the consistency of the light intensity during the test, the test should be carried out after the light source was stable (after about 30 minutes).
- Step 2: Adjust the position of CMOS image sensor. The CMOS image sensor was placed in the darkroom of the test vehicle. The CMOS chip should be located at the center of the export of uniform light, at the same time, adjusting the distance between CMOS image sensor and photometric integrating sphere to meet the standard. Turn off the darkroom to prevent interference from outside light.
- Step 3: Set the offset of CMOS image sensor and the number of captured images. The value of offset control the number of zero value pixel less than 0.5% of the total pixel of CMOS image sensor, which ensure dark signals containing temporal noise and spatial un-uniformity cause little cutoff. The number of captured images is set to 100, because the average of all captured images can suppress the interference of temporal noise to spatial un-uniformity.
- Step 4: Turn on the power supply module. The CMOS image sensor was driven, and the optical signal was converted into electrical signal. Adjust the intensity of uniform light and the exposure time appropriately to make the pixel mean value of CMOS image sensor reach to 50% of the saturation [8].
- Step 5: Store the captured images. Then in the next chapter, the column FPN of the CMOS image sensor was estimated by AR-NPS method using the captured images.

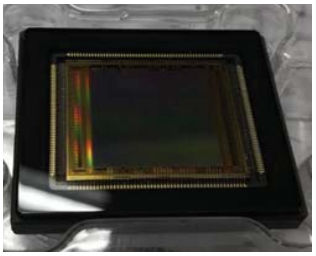

Figure 4. The specific CMOS image sensor.

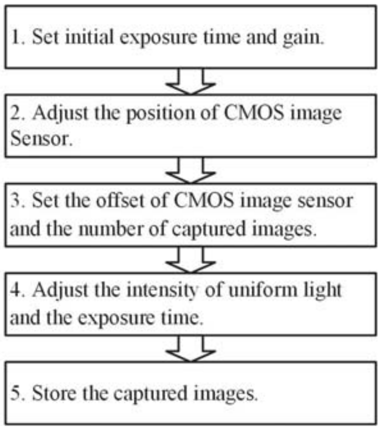

Figure 5. Test flow of CMOS image sensor.

For our tests, the exposure time was adjusted to 9.61 (ms) and the gain was set to 2.4. We acquired 100 images under the same uniform light and exposure time. The sample of the images is shown in Fig. 6.

Figure 6. The sample of the images.

IV. EVALUATION OF COLUMN FPN

The images captured by the CMOS image sensor contains mixed noise, including DN, RN and FPN. In order to evaluate the noise level of column FPN accurately, the extraction method of column FPN was studied to suppress the interference of DN and RN. Then, the AR-NPS method was proposed to estimate the column FPN of CMOS image sensor.

A. Extraction of column FPN

We used the multi-frame averaging method to suppress DN and RN in this paper [9]. Ideally, the pixel value of each images captured by CMOS image sensor is the same. In practice, because of the existence of noise, the pixel value will be caused deviated, so the standard deviation of pixel value can represent the level of noise. The principle of the multi-frame averaging method is as follow：

The image can be represented by a two-dimensional function, and noisy image can be expressed as the superposition of noiseless image and random noise. Thus：

$$f(x,y) = g(x,y) + n(x,y) \tag{1}$$

As in (1), $f(x,y)$ is the noisy image, $g(x,y)$ is the noiseless image, $n(x,y)$ is the random noise.

The variance of the image averaged by multiple images is as follows:

$$\sigma_f\left(x,y\right) = \frac{1}{N}\sigma_\eta^2\left(x,y\right) \tag{2}$$

As in (2), $\sigma_f(x,y)$ is the variance of single image.

From (1) and (2), the variance of multi-image averaging method is $1/N$ of the original image. With the increase of the pixel value, the variance of the image decreases.

Based on the multi-frame averaging method, we used the 100 captured images which of the pixel value had been averaged to extract the column FPN. The sample of image after extraction is shown in Fig. 7. This process can be described in the following expression:

$$f_N\left(x,y\right) = \frac{1}{N}\sum_{i=1}^{N} f_i\left(x,y\right) \tag{3}$$

As in (3), $f_N(x,y)$ is the pixel value after averaging N images, $f_i(x,y)$ is the pixel value of the ith image, and N is the total number of images.

Figure 7. The sample of image after extraction.

The noise power spectrum method based on AR model is mainly used in one-dimensional noise estimation. Based on the characteristics of column FPN, the gray value of the pixels in a row is inconsistent [10]. That is, the difference between the gray values of the different row is large, the gray value of the column is almost the same. Therefore, the average gray value of each column can represent the gray value of the column, which is used to reduce the dimensionality of the two-dimensional image. The dimension reduction process can be described in the following expression:

$$f_Y(x,y)=\frac{1}{Y}\sum_{y=1}^{N} f_N(x,y) \quad (4)$$

As in (4), $f_N(x,y)$ is the pixel value after averaging N images, $f_Y(x,y)$ is the pixel value after averaging Y rows of $f_N(x,y)$, and Y is the total rows of the image.

B. Evaluation of column FPN Using AR-NPS

AR model is an autoregressive model, also known as all-pole model. It can be expressed by the following difference equation [11]:

$$x_n=-\sum_{i=1}^{p} a_i x_{n-i}+\mu_n \quad (5)$$

As in (5), μ_n is a white noise sequence with zero mean and σ^2 variance, P is the order of AR model, and a_i is the parameter of order AR model.

The parameters of AR model are related to the autocorrelation function x_n of $R_x(m)$ as follows:

$$R_x(m)=\begin{cases}-\sum_{i=1}^{p} a_p(i)r_x(m-i), & m\ge 1\\ -\sum_{i=1}^{p} a_p(i)r_x(i)+\sigma^2, & m\ge 1\end{cases} \quad (6)$$

As in (6), $r_x(i)$ and $r_x(m\text{-}i)$ are the variable of the equation, $a_p(i)$ is the coefficient of the equation.

The parameters in AR model can be solved by autocorrelation algorithm, then the noise power spectrum of AR model can be obtained. First, the autocorrelation function of the observed data was obtained. Then, according to the recursive nature of the yule-walker equation, the model parameters were obtained by using L-D recursive algorithm [12]. Finally, the noise power spectrum estimation of the fixed mode was obtained by combining with the noise power spectrum expression of the AR model.

The L-D recurrence formula is as follow：

$$\begin{cases} a_m(m)=-\left[r(m)+\sum_{k=1}^{m=1} a_{m-1}(k)r(m-k)\right]/\sigma_{m-1}^2 \\ a_m(k)=a_{m-1}(k)+a_m(m)a_{m-1}(m-k), \\ \sigma_k^2=\left(1-\left|a_m(m)\right|^2\sigma_{k-1}^2\right),\sigma_0^2=r(0) \\ k=1,2,\cdots,m-1 \end{cases} \quad (7)$$

As in (7), a_m is the parameter of order AR model, $r(m)$ is the variable of $R_x(m)$.

The equation of the noise power spectrum based on AR model is as follow:

$$\mathrm{NPS}(\omega)=\frac{\sigma^2}{\left|A\left(e^{j\omega}\right)\right|^2}=\frac{\sigma^2}{\left|1+\sum_{i=1}^{p} a_i e^{-j\omega i}\right|^2} \quad (8)$$

As in (8), a_i is the parameter of order AR model, σ^2 is the variance of a white noise sequence.

Based on the captured images, we used AR-NPS method to estimate the column FPN of CMOS image sensor. The result is shown in Fig. 8. The noise power of column FPN fluctuates between -80 and 0 dB with a peak of 250 Hz.

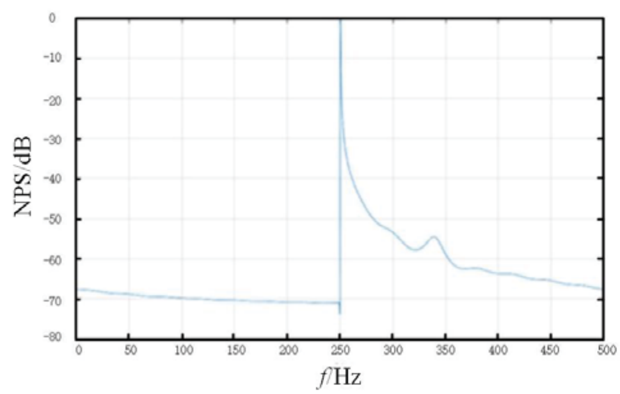

Figure 8. The result of column FPN evaluation using AR-NPS

V. CONCLUSION

In this paper, it mainly studied the evaluation method of column FPN of CMOS image sensor. Firstly, we introduced the structure of the test vehicle, and built it to capture images of CMOS image sensor. Secondly, we designed the test flow of the CMOS image sensor by using the test vehicle to capture images based on the EMVA Standard 1288, and used a specific CMOS image sensor acquiring a series of images. Then, we used the multi-frame averaging method to extract the column FPN of CMOS image sensor. Finally, we used the AR-NPS method to estimate the column FPN.

The proposed column FPN estimation method can provide an evaluation of spatial noise dimension while considering selection of CMOS imagers. And it can also be utilized to evaluate the achievement of improving the performance of CMOS image sensors.

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