Simplified Fixed Pattern Noise Correction for Logarithmic Sensors

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***Abstract*—**
The quality of images from high dynamic range logarithmic sensors is severely degraded by Fixed Pattern Noise (FPN), caused by a non-uniformity in the responses of individual pixels. The source of this fixed pattern noise has been explained by Joseph and Collins [1] using a model which represents the response of each pixel in terms of three parameters - an offset voltage, a gain and a leakage current in each pixel. Previously, the proposed model has been used to explain the response of pixels and the origins of fixed pattern noise. However, it has not been used to create a practical fixed pattern noise correction procedure. In this paper a simple and practical procedure to correct for fixed pattern noise in logarithmic sensors for high dynamic range scenes is developed. The results are images with contrast sensitivities comparable to that of the human visual system in high illumination.

***Index Terms*—Fixed Pattern Noise (FPN), Offset and Gain Correction, Parameter extraction, FPN Modelling.**

I. Introduction

The human visual system has the ability to interpret scenes with illuminations varying from 1×10^{-3} lux to 1×10^{5} lux. Typical real world scenes have dynamic intra-scene range that might extend about five orders of magnitude, from 1 lux in shadows to 1×10^{5} lux of bright sunlight [2]. Unfortunately, charged coupled devices (CCD's) and CMOS ative pixel sensors (APS), which dominate the image sensor market have a dynamic range of less than three orders of magnitude. Consequently, when imaging a wide dynamic range natural scene the response of these sensors saturates in some regions of the scene. Despite several techniques to increase this dynamic range both, in-pixel [3], [4], [5] and post capture [6], the overall performance of the sensor is greatly diminished due to increased fill factor and circuitry to accommodate the corresponding extra functionality.

Logarithmic image sensors based upon the subthreshold region of operation of a MOS are capable of capturing wide dynamic range scenes, with intensity variations of more than six decades [7], [8]. In addition, these sensors provide random addressability and use a comparatively small number of bits per pixel while retaining a fill factor comparable to that of CMOS Active Pixel Sensors. Another potential advantage of logarithmic pixels is that they encode the contrast information from a scene that is critical to users. However variations between devices within different pixels causes this type of sensor to suffer from fixed pattern noise (FPN) that severely degrades the quality of the resulting image.

Unfortunately, since logarithmic sensor operation is continuous it is impossible to use techniques such as correlated double sampling (CDS) widely used in linear APS sensors for the fixed pattern noise reduction. Several different approaches to reduce FPN in logarithmic imagers have therefore been proposed. In this paper, different methods of performing fixed pattern noise correction on the output from logarithmic pixels are compared.

One advantage of using logarithmic pixels is that their output represents the contract information that is critical to both an observer and automatic object recognition systems. The quality of images required from a pixel array will depend upon the application. For this initial study the performance of each procedure is therefore compared to the human visual system. In particular, the standard deviation of the response of a group of pixels to a uniform stimulus after fixed pattern noise correction is compared to the contrast sensitivity of the human visual system. The human visual system has a contrast sensitivity of approximately 1% at high illuminations [9]. The aim when developing a FPN correction procedure is therefore to ensure that, the standard deviation of the corrected pixel responses to a uniform stimulus, is less than the change in response of an average pixel when its input changes by 1%.

The rest of the paper is organised as follows. Section II is a short description of the logarithmic pixel circuit. The effectiveness of different approaches to offset FPN correction are then investigated in Section III. The disappointing results obtained using even the best offset correction technique means that it is necessary to consider techniques that correct for offset and gain variations. A simple procedure is described in section IV that achieves a contrast sensitivity comparable to the human visual system over a wide input dynamic range.

II. The Pixel

The offset correction technique recommended with the Fuga 15d [6] logarithmic camera required the user to image a uniform scene (generated with a piece of white paper). This image was then stored and subtracted from all subsequent images to correct for the dominant fixed pattern noise. Although this procedure dramatically improved the quality of the final image, generating the uniform scene whenever the operating conditions of the camera changes can be very inconvenient for the user.

The inconvenience of creating a uniform stimulus optically can be avoided by generating a uniform electronic stimulus. The two approaches of this type that have been suggested previously are based upon providing a high input current [7], [10] or shorting the terminals of the photodetector to create a very small input current [11]. In the pixel shown in Figure 1 the uniform stimulus for fixed pattern noise correction is provided by the current flowing through transistor $M6$. This transistor is located at the end of a column of pixels and when necessary its drain can be connected to any one of the pixels in the column. The effectiveness of using a constant current source for fixed pattern noise correction has been investigated for pixels fabricated on an unmodified 0.35 micron CMOS process. Using this process it is possible to create pixels with an area of $10\mu m \times 10\mu m$ pixels having 49% fillfactor. The readout circuit in this pixel was changed from the conventional source follower to a differential amplifier to increase the overall sensitivity of the pixel. The result is a pixel whose output voltage changes by $45mV$ when its input changes by an order of magnitude. This means that a 1% change in the input will cause a change in the output voltage of $0.2mV$.

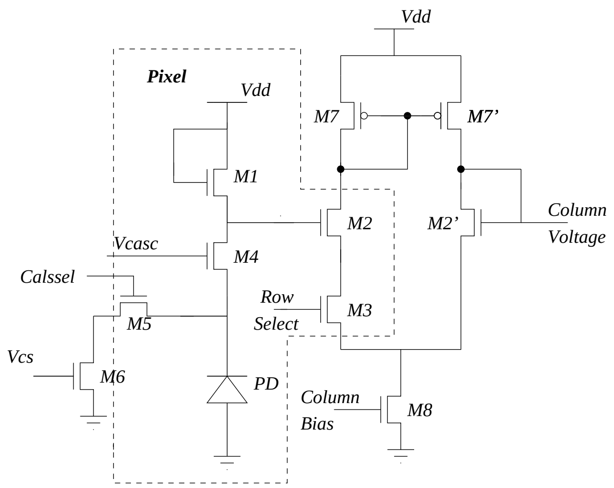

Fig. 1. A figure showing the pixel, differential readout and calibration circuitry used to electronically generate image data.

III. Offset Correction

The effectiveness of various offset fixed pattern noise correction procedures has been assessed using the responses of a column of 100 pixels at 23 different currents covering more than 10 decades. The first two techniques that were tested replicated the approaches adopted by Kavadias and co-workers [7], [10] and Lai and co-workers [11]. These results showed that using either a very high or a very low current during calibration leads to disappointing results.

To understand the disappointing results obtained using these two procedures consider the response of a typical pixel shown in Figure 3. As expected this data shows that the pixel has a logarithmic response. However, this response only occurs over an input range of approximately 5 decades centered around $100pA$. For input currents below this range the sensitivity of the pixel is decreased by the effects of a leakage current in the pixel. In contrast for higher photocurrents the sensitivity of the pixel increases when the load transistor $M1$ is forced into moderate rather than weak inversion. Unfortunately, this increase in sensitivity is associated with a departure from a logarithmic relationship between the input current and the output voltage. The

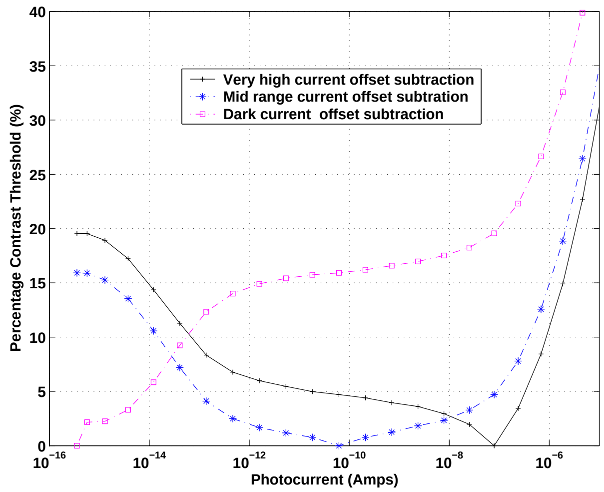

Fig. 2. Graphical comparison of some offset FPN correction techniques against percentage contrast threshold. The photocurrent axis is obtained by using a circuit simulator (CADENCE) to acquire the corresponding photocurrents that the pixel circuit in Figure 1 would generate, if the photodetector were illuminated.

response of a pixel in both weak and moderate inversion in the presence of a leakage current can be represented using a four parameter model [12]

$$y = a + b \ln \left(\exp(\sqrt{c + dx}) - 1 \right) \quad (1)$$

Therefore, the leakage current and moderate inversion effects prevent successful fixed pattern noise correction using the response of pixels at either a low or a high current.

The effects of both leakage currents and moderate inversion can be minimised by using the response of the pixel from the centre of its logarithmic response region to correct for fixed pattern noise. The results in Figure 2 show that using this data to perform fixed pattern noise correction will dramatically improve the quality of the final image. However, even with this technique the quality of the corrected image will degrade when the photocurrent varies from the value used for fixed pattern noise correction.

The degradation in the effectiveness of fixed pattern noise correction can be understood using a model for the response of a logarithmic pixel. When the photocurrent x_i is larger than the leakage current and the load transistor is operating in weak inversion the four parameter model for the response of pixel j in equation (1) reduces to

$$y_{ij} = a_j + b_j \ln(x_i/x_{scale}) \quad (2)$$

where a_j and b_j are the offset and gain of pixel j and x_{scale} is a constant. This means that the response of this pixel to a calibration current x_c is

$$y_{cj} = a_j + b_j \ln(x_c/x_{scale})$$

Subtracting this calibration response from all subsequent responses will give

$$y_{ij} - y_{cj} = b_j \ln \left(\frac{x_i}{x_c} \right) \quad (3)$$

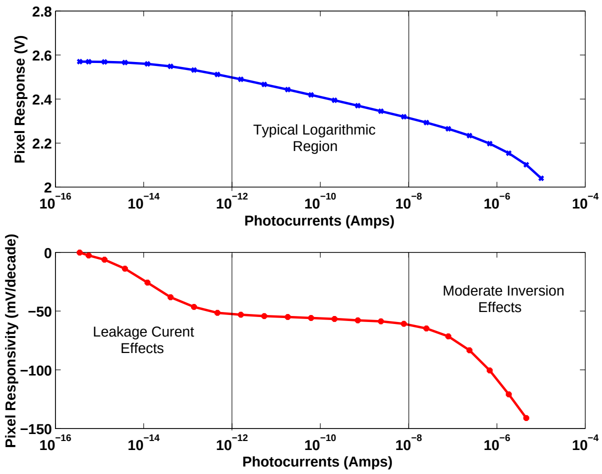

Fig. 3. A plot showing the typical response curve of an electronically stimulated pixel (top) and its corresponding responsivity in mV per decade (bottom) over a wide dynamic range. The three regions are critical and determine the success of offset subtraction FPN correction techniques

As required this result is independent of the offset of each pixel and this dominant form of fixed pattern noise will therefore be removed from an image. However, the corrected response of each pixel depends upon its gain, b_j. Any variations between the gains of the different pixels will cause fixed pattern noise in this corrected image.

IV. Offset and Gain Correction

The contribution of gain variations to fixed pattern noise has been confirmed by using least square error minimisation to fit the response of each pixel to a mean pixel response[1]. As expected the standard deviation of the offset parameter extracted using this procedure, $22.6mV$, confirmed that variations in this parameter are the dominant source of fixed pattern noise. However, this data also showed that the standard deviation of the gain parameter 0.44% is consistent with a contrast threshold sensitivity of approximately 1% when the photocurrent is a decade smaller or larger than the calibration current. Comparison of this estimate with the results from simple offset correction, shown in Figure 4, suggest that after offset correction the dominant contribution to fixed pattern noise is gain variations. To confirm this hypothesis the offset and gain parameters from each pixel obtained by error minimisation have been used to correct fixed pattern noise in the data from the column of pixels. The results obtained using these parameters to correct for both offset and gain variations, Figure 4, show that correcting for both types of variations dramatically improves the quality of the final image over a wide input dynamic range. Furthermore, correcting for both the offset and gain variations leads to a percentage contrast threshold that is better than that of the human visual system.

Although least square error minimisation can be used to validate a model or confirm the role of gain variations it is too computationally demanding to be used in a fixed pattern noise correction procedure. A simpler procedure to obtain the two parameters for each pixel is therefore required. This procedure can be developed by considering the two parameter model for the pixel response

$$y_{ji} = a_j + b_j \ln(x_i/x_{scale}) \quad (4)$$

Since this equation contains two parameters per pixel, a_j and b_j, at least two data points will be required to obtain the parameters in this equation.

Once again to compensate for additive variations between pixels the response of each pixel y_{jc_1} to a calibration current x_{c_1} can be subtracted from the subsequent response of the same pixel to give

$$y_{ji} - y_{jc_1} = b_j \ln(x_i/x_{c_1}) \quad (5)$$

If the pixel responses at a second calibration current x_{c_2} are then measured it will be possible to measure the gain of each pixel. However, obtaining the absolute value of the gain would require a measurement of the two calibration currents. Any measurement of the currents used to characterise a pixel can be avoided by transforming the response of each pixel to correspond to the response of an average pixel.

To transform the response of each pixel to the equivalent response of an average pixel consider the average pixel response of a group of pixels, in this case a column of pixels, at photocurrents x_{c_1} and x_{c_2}

$$\bar{y}_{c_1} = \bar{a} + \bar{b}\ln(x_{c_1}/x_{scale}) \quad (6)$$
$$\bar{y}_{c_2} = \bar{a} + \bar{b}\ln(x_{c_2}/x_{scale}) \quad (7)$$

This means that the average gain of the pixels is

$$\bar{b} = \frac{\bar{y}_{c_1} - \bar{y}_{c_2}}{\ln(x_{c_1}/x_{c_2})}$$

Similarly, the gain of pixel j is

$$b_j = \frac{y_{jc_1} - y_{jc_2}}{\ln(x_{c_1}/x_{c_2})}$$

hence the gain of each pixel can be defined relative to the average gain

$$b_j = br_j \times \bar{b}$$

where

$$br_j = \frac{y_{c_1 j} - y_{c_2 j}}{\bar{y}_{c_1} - \bar{y}_{c_2}} \quad (8)$$

Substituting Equation 8 into Equation 5 leads to

$$y_{ji} - y_{jc_1} = br_j \bar{b} \ln \frac{x_i}{x_{c_1}} \quad (9)$$

This equation can then be rearranged to give

$$\frac{y_{ji} - y_{jc_1}}{br_j} = \bar{b} \ln\left(\frac{x_i}{x_{c_1}}\right) \quad (10)$$

which shows that the response of the pixel can be transformed to the equivalent response of a pixel with an offset of zero and a gain that is equal to the average gain $\bar{b}$.

Equation (10) was derived assuming that the response of the pixel can be represented using a two parameter model. However, the results in Figure 3 show that this model is only valid over a range of approximately five decades. The quality of fixed pattern noise correction achieved using Equation (10) therefore depends upon the choice of the two calibration currents. This choice has been investigated by Otim and co-workers [12]. They showed that the lower of the two calibration currents should be chosen so that it is two orders of magnitude larger than the leakage current. Then the higher calibration current should be chosen to be two orders of magnitude below the current corresponding to the transition between the load transistor operating in weak and moderate inversion.

This calibration current selection criteria has been employed in a simple procedure to extract the relative gain parameter needed to correct for variations between the gains of different pixels. As expected the parameters extracted using the data from two calibration currents were very similar to the values obtained using least square error minimisation. It is therefore not surprising that the results in Figure 4 show that correcting for gain and offset variations using the parameters obtained by either technique leads to a significant improvement in the quality of images compared to simple offset correction. A comparison of the results using the two different sets of parameters shows that the more sophisticated parameter extraction technique gives a better performance. However, even the parameters obtained using a simple procedure based upon the response of the pixels to two calibration currents gives a contrast threshold less than that of the human visual system over a wide input dynamic range. Since this performance is achieved whilst avoiding the computations required to perform least square error minimisation the simple parameter extraction procedure is the simplest method of correcting for offset and gain variations.

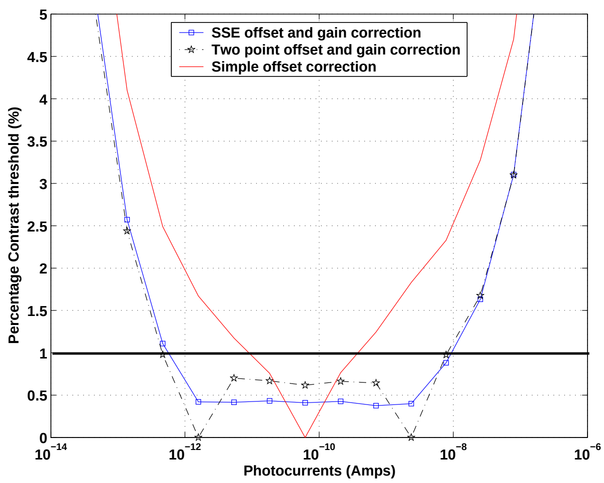

Fig. 4. Performance comparison of two offset and gain correction techniques. Even over a four decade dynamic range, a contrast threshold of 1% is easily achieved.

V. Conclusion

Fixed pattern noise exists as a result of device mismatches in pixel and readout circuits causing a reduction of image quality. Fixed pattern noise correction based upon calibrating the pixels at a minimum number of currents has been investigated. Initially, previously described procedures based upon using the response of each pixel to a very small or a very large current to compensate for additive fixed pattern noise were investigated. The disappointing results obtained by both these procedures were explained by a model of the response of each pixel. This suggested that this type of procedure should be based upon the response of each pixel to a typical, rather than an atypical, current. Although using a typical current leads to a significant improvement in image quality the results were still disappointing compared to the performance of the human visual system. The reason for this disappointing result is that the gains of the pixels also vary. A simple procedure to extract the gain of each pixel has been described. By using the parameters obtained from this procedure it is possible to compensate for offset and gain variations by transforming the response of each pixel to the equivalent response of an average pixel. The result is a system with a high dynamic range and a contrast sensitivity comparable to that of the human visual system.

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