AN ELECTRONIC CALIBRATION SCHEME FOR LOGARITHMIC CMOS PIXELS

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ABSTRACT

Logarithmic cameras have the wide dynamic range required to image natural scenes and encode the important contrast information within the scene. However, the images from these cameras are severely degraded by fixed pattern noise. Previous attempts to improve the quality of images from these cameras by removing additive fixed pattern noise have lead to disappointing results. Using a three parameter model for the response of logarithmic pixels, it is concluded that the residual fixed pattern noise in these images is caused by gain variations between pixels. In order to reduce the effects of these variations a new type of readout circuit has been designed. However, even with this readout circuit high quality images will only be obtained if each image is corrected to remove the effects of both gain and offset variations. Measurement results are presented that show that the quality of the output from logarithmic pixels is significantly improved if a procedure is used which corrects for both types of variations. In fact with this procedure the contrast sensitivity of the logarithmic pixels becomes comparable to that of the eye over five decades of input illumination intensity.

1. INTRODUCTION

Logarithmic image sensors designed in CMOS technology are capable of capturing wide dynamic range scenes, with intensity variations of more than 6 decades [1]. 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 mean that this type of sensor suffers from fixed pattern noise(FPN), that severely degrades the quality of the resulting image.

The dominant form of fixed pattern noise is an additive offset contribution whose impact can be reduced using one of a variety of different techniques described in section 2. In section 3, the disappointing results obtained using these techniques are explained using a model for the response of these pixels [2]. This model suggests that variations between the gains of pixels should be taken into account when correcting fixed pattern noise.

A procedure to extract the gain and offset parameters of each pixel is then proposed. To implement the scheme the response of each pixel must be determined at three different inputs. A new pixel circuit is then described which has been designed to reduce both the effects of gain variations and to allow the response of each pixel to be measured under different operating conditions. Experimental results are then presented which show that after fixed pattern noise correction these pixels have a contrast sensitivity which is comparable to that of the eye over an input range of five decades [7].

2. PREVIOUS WORK

The major contribution of fixed pattern noise comes from variations between the threshold voltages of the transistors in the different pixels. This has lead to the development of various techniques to reduce effects of this additive fixed pattern noise. The ideal approach to tackling this problem is to change each pixel so that they have a more uniform response. One method of achieving this that has been investigated, is the use of hot electron effects within each pixel to alter the threshold voltage of the load transistor [3]. This technique has been successfully applied to a small number of pixels. However, even when high stressing voltages are applied to increase the number of hot electrons available this proved to be a time consuming process. In an alternative approach Loose and coworkers [4], have used feedback to adjust the gate voltage of each load transistor. This technique has the advantage that it avoids the slow process of adjusting the threshold voltage of the device. It can accommodate changes in the offset voltage due to the temperature dependence of the threshold voltage of the various transistors. However, the additional circuitry required to use this technique increases the pixel area and reduces fill-factor.

The difficulties involved in creating pixels with more uniform responses has lead to the development of techniques

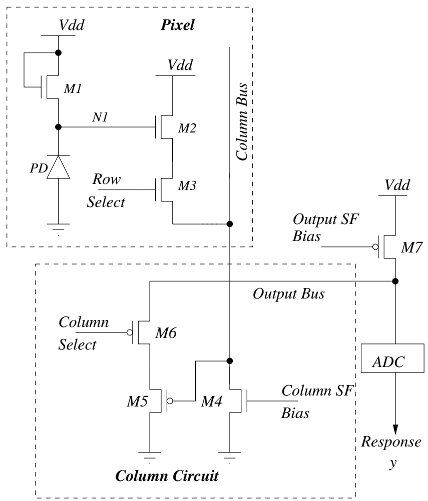

Fig. 1. *A Logarithmic Pixel with Source Follower Readout*

in which the image is corrected after it has been acquired. In the case of correcting for fixed pattern noise this means that the response of each pixel to a uniform input has to be measured. The most direct method of obtaining the data required to correct for additive fixed pattern noise is to image a uniform scene [5, 6]. Unfortunately, the temperature dependence of the transistor threshold voltages means that this procedure must be undertaken whenever the operating temperature of the camera changes. This is inconvenient to do in a laboratory environment, and it might be impossible to implement in many applications. To avoid the need to provide a uniform input scene an alternative scheme was proposed by Kavadias and coworkers [1]. In this scheme the offset of each pixel is determined by forcing a constant current through the load transistor using a MOSFET acting as a constant current source that is connected in parallel with the photodiode. Using the resulting data to correct for offset variations leads to a residual fixed pattern noise that is 2.5% rms of the total dynamic range of the data. Since the dynamic range of the data is six decades, this corresponds to 15% of one decade. This is a very disappointing contrast sensitivity.

3. ELECTRONIC CALIBRATION

The high residual FPN in the images captured by Kavadias and coworkers can be understood by considering a model of the response of a logarithmic pixel. By considering the characteristics of the devices within a logarithmic pixel, Joseph and Collins have shown that the response of a logarithmic pixel, y to a photocurrent x, can be written in the form[2]

$$y = a + b\ln(c + x) \tag{1}$$

In this equation a represents an additive offset voltage that is the dominant source of fixed pattern noise. However, there are also two other parameters, the pixel gain b, and a parameter c, that represents the effects of a leakage current within the pixel. The most important effect of this third term is to limit the sensitivity of each pixel at low illumination levels. At higher photocurrent the effects of this term are negligible. In these situations the response of the photocurrent can be accurately approximated by

$$y = a + b\ln(x) \tag{2}$$

Forcing a constant current, x_c, through the load transistor of each pixel will lead to a pixel response y_c. Subtracting this from the pixel response at an unknown current x_{in} will then lead to a corrected output y_{corr}

$$y_{corr} = b\ln(x_{in}/x_c) \tag{3}$$

When the input scene is uniform, the current through all the pixels will be the same. However, the corrected output will only be the same if all the pixels have the same gain. Unfortunately, variations between the devices within each pixel lead to gain variations. It is this effect that could be responsible for the poor performance obtained by Kavadias and coworkers.

In order to quantify the effects of gain variations consider a pixel whose gain b differs from the mean pixel gain $\bar{b}$ by Δb. With offset correction this gain variation will lead to an error in the corrected output of

$$\Delta y_{corr} = \Delta b\ln(x_{in}/x_c) \tag{4}$$

The equivalent percentage error in the apparent contrast of this pixel, K, is then given by

$$K = \frac{100\,\Delta b}{\bar{b}}\ln(x_{in}/x_c) \tag{5}$$

The effects of gain variations can be limited by either reducing the percentage variation in the gain or using a typical photocurrent as the reference current for offset correction. However, high quality images will only be achieved over a wide dynamic range by correcting for offset and gain variations.

In order to correct for variations in the offset and gain of each pixel a technique is required to determine the value of these two parameters for each pixel. When demonstrating the validity of the three parameter model Joseph and Collins used data from twenty four uniform images at different illumination levels and an iterative parameter extraction technique. It is impractical to use this technique to obtain the data required to correct an image for fixed pattern noise. However, there are only three parameters in the model and these parameters can therefore be estimated using three data points per pixel. Obtaining these data points electronically will make fixed pattern noise correction convenient for the user.

The other advantage of electronic calibration is that the reference currents used to obtain the data for parameter extraction can be selected to simplify the parameter extraction procedure. For example, for the calculation of the offset and gain of each pixel, two of the reference currents should be chosen so that they are much larger than the leakage current in each pixel. Under these conditions the contribution of c becomes negligible. Then if the pixel response at reference current x_1 is y_1 and its response to another current x_2 is y_2 the two parameters can be calculated using

$$b = \frac{y_1 - y_2}{\ln(x_1/x_2)} \quad (6)$$

$$a = y_1 - b\ln(x_1) \quad (7)$$

The value of the third parameter c is then best determined using a data point from the operating region in which the leakage current is larger than the photocurrent. Therefore the best data to use to obtain this parameter is when the only current flowing through the load transistor is the leakage current. This data point corresponds to the dark response, y_d of the pixel and since at this point $x = 0$

$$c = \exp(\frac{y_d - a}{b}) \quad (8)$$

This parameter can then be used to characterise the minimum illumination level at which the pixel gives a logarithmic response.

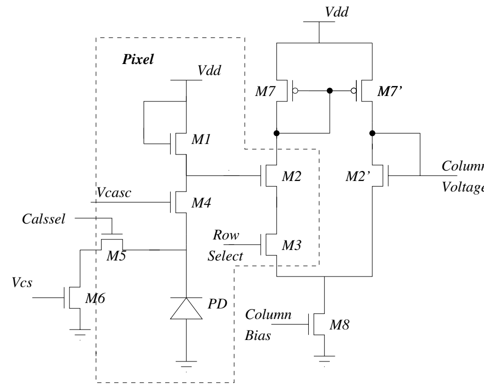

Fig. 2. A Logarithmic Pixel with One Stage of a Differential Amplifier Readout and Electronic Calibration

Parameter	Mean/SD	SF	Diff.Amp.
Offset	Mean	0.5524	1.7430
(V)	SD	0.0165	0.0174
Gain	Mean	-56.87	-66.7
(mV/decade)	SD	1.084e-3	1.023e-3
Bias	Mean	28.163	26.188
(fA)	SD	4.4974	6.3040

Table 1. Comparison of statistical parameters of one stage of source follower(SF) and differential amplifier(diff amp) readouts

4. CIRCUIT IMPLEMENTATION

A logarithmic pixel that can be calibrated electronically is shown in figure 2. In this circuit transistor $M1$ is the load device that converts the photocurrent to a voltage. Transistor $M4$ was included in the pixel to limit the voltage across the photodiode while transistor $M5$ acts as a switch. This switch can be used during calibration to selectively connect the pixel to the drain of transistor $M6$ which acts as the voltage controlled current source. In order to save area and to ensure uniformity of the current flowing in different pixels, this device is shared by all the pixels in the same column.

In a conventional logarithmic pixel a source-follower circuit is used as the readout circuit. The problem with this simple circuit is that it has a relatively low gain. This can be a problem for logarithmic pixels which typically have a sensitivity of approximately 70 mV/decade. In order to minimise any attenuation of the resulting small signals by the readout circuit the source-follower has been replaced by a differential amplifier. In this circuit, the two pMOS transistors form a current mirror and transistor $M8$ acts as a constant current source. Assuming that the on resistance of transistor $M3$ is zero and that the current mirror is ideal, then the gate-source voltages of transistors $M2$ and $M2'$ will be equal. In these circumstances this circuit acts as a voltage follower. This circuit therefore can have a significantly higher gain than the alternative source-follower circuit. In addition, since only transistors $M2$ and $M3$ are actually within each pixel, this increased gain can be achieved without increasing the area of the pixel.

Logarithmic pixel circuits with source-follower or differential amplifier readout circuits have been manufactured on a standard 0.35 micron CMOS process. Each pixel had an area of $10\mu\times10\mu$, with a fill factor of 58 %, designed to form an array of 100×10 pixels. In order to determine the variability between the different pixel responses, these two pixel arrays have been tested using spatially uniform scenes.

To compare the performance of the two different pixel designs the mean and standard deviation of each of the three extracted pixel parameters was calculated from this data. The results in Table 4 show that as expected there is a significant difference in the mean offset voltage of the two designs arising from the voltage drop across the source-follower. In addition there appears to be very little difference in the leakage current in the two type of pixels. This means that both types of pixel will only respond once the

Pixel Current(A)	Residual FPN	Contrast Sensitivity
3.55e-13	0.922	2.11
1.07e-12	0.694	1.62
3.91e-10	0.397	0.92
8.80e-10	0.440	1.10
3.25e-9	0.429	0.99
3.45e-8	0.501	1.16
1.57e-7	1.089	2.53

Table 2. Residual rms FPN expressed as percentage of signal swing per decade of light intensity and contrast sensitivity after 2 parameter calibration

illumination level increases about 0.2 lux. The most important difference in the mean parameter values is an increase in the pixel gain from 56.9 mV/decade with a source-follower to 66.7 mV/decade when a differential amplifier readout circuit is used. In addition the variability of the gains of the two types of readout circuits are comparable. The larger gain of the differential amplifier readout circuit means that the gain variations in these pixels will give rise to a smaller contribution to fixed pattern noise. Significantly, because only two of the transistors within the differential amplifier circuit are within each pixel, this improvement has been achieved without increasing the area of the pixel.

4.1. Calibration Results

Over a wide dynamic range, the effects of the leakage current are negligible. In this operating region the response of each pixel can be characterised by an offset and a gain. The effectiveness of a technique to correct both these sources of fixed pattern noise has been assessed on a sample of 180 pixels manufactured on an $0.35\mu m$ process.

Two data points per pixel are required to correct images for both offset and gain variations. The current source in figure 2 was therefore used to determine the response of each pixel when its load transistor was forced to source 51 pA and 11 nA. These two measured responses from each pixel were then used to determine both the offset and the gain of each pixel. With this information the responses of the pixels at seven other currents, over a range of more than six decades, have been corrected in order to reduce the fixed pattern noise. The results in Table 2, show that over an input range of five decades the residual fixed pattern noise is equivalent to a contract sensitivity of less than 2%. This is an improvement of more than an order of magnitude on the results obtained by Kavadias and coworkers. More importantly, this form of fixed pattern noise correction improves the contrast sensitivity of the pixels so that it is comparable with that of the eye over a wide dynamic range.

5. CONCLUSION

Variations between devices in pixels of a logarithmic camera degrade the quality of the image produced. Thus, despite the capability of imaging wide dynamic range scenes and encoding the important contrast information, these cameras have poor performance.

Previous attempts to improve quality of the images from these cameras have concentrated upon correcting an additive form of fixed pattern noise. Although this is the largest component of fixed pattern noise the results have been disappointing. A three parameter model for the response of logarithmic pixels that has been proposed previously, suggests that the problem with this previous work is that it ignores variations in between the gain of individual pixels. A new type of readout circuit has been investigated that reduces the significance of these gain variations. However, high quality images will only be obtained if each image is corrected for both gain and offset variations. Measurements results have been presented that show that correcting for both types of variations significantly improves the quality of the output image. In fact the results are comparable to the contrast sensitivity of the eye over five decades of input illumination intensity.

6. REFERENCES

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