Fixed Pattern Noise Correction for Wide Dynamic Range Linear-Logarithmic Pixels

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*Abstract***—**
Pixels with the capability of linear response in low light regions and logarithmic response at high intensity have been proposed previously. A model for the complex response of these pixels has been devised that can be used to study the origins of fixed pattern noise and develop a fixed pattern noise correction procedure. The problem with correcting the fixed pattern noise in these pixels is the transition region between the linear and logarithmic operating regions. One way to avoid the problems from the transition region is to capture two outputs at different integration times within the same exposure. The resulting data can then be corrected for fixed pattern noise and converted to an equivalent linear or logarithmic response for subsequent image processing.

I. INTRODUCTION

The recent commercial success of digital cameras has been achieved despite the fact that the dynamic range of the commercially successful cameras is smaller than the dynamic range of many scenes. However market saturation has increased the demand for differentiation. One possible means of differentiation is to increase the dynamic range of the camera. Logarithmic response image sensors have been proposed to capture the wide dynamic range present in nature, by compressing the input dynamic range. The problem with these pixels is that their performance is degraded at low light levels by the dark current that flows through each pixel. A logarithmic pixel with a reduced dark current has been described previously [1]. To improve the speed of response and sensitivity of this pixel at low light levels, it can be operated in a mode that produces a linear output at low light levels and a logarithmic output at higher light levels (referred to as LLCMOS for convenience). Similar responses have also been reported by Fox, et.al. [2] and Martin [3].

In common with all pixels, these pixels suffer from fixed pattern noise caused by unavoidable variations between the identical devices in different pixels. A model for the complex response of these pixels has been used to characterise the fixed pattern noise in an array of these pixels [4]. In this paper, a simple yet effective fixed pattern noise correction procedure for these pixels is developed. Section II describes the pixel, its operation and the response model. The simplest FPN correction procedure for LLCMOS pixel would include standard FPN correction routines for linear and logarithmic pixels. However, special procedure needs to be devised for the transition region. Section III presents such a procedure. However, the residual FPN is found to be high owing to uncorrected temporal noise in this region. Section IV presents one way to avoid the problems from the transition region by capturing two outputs at different integration times within the same exposure. The final section summarises the conclusion.

II. LINEAR LOGARITHMIC PIXEL

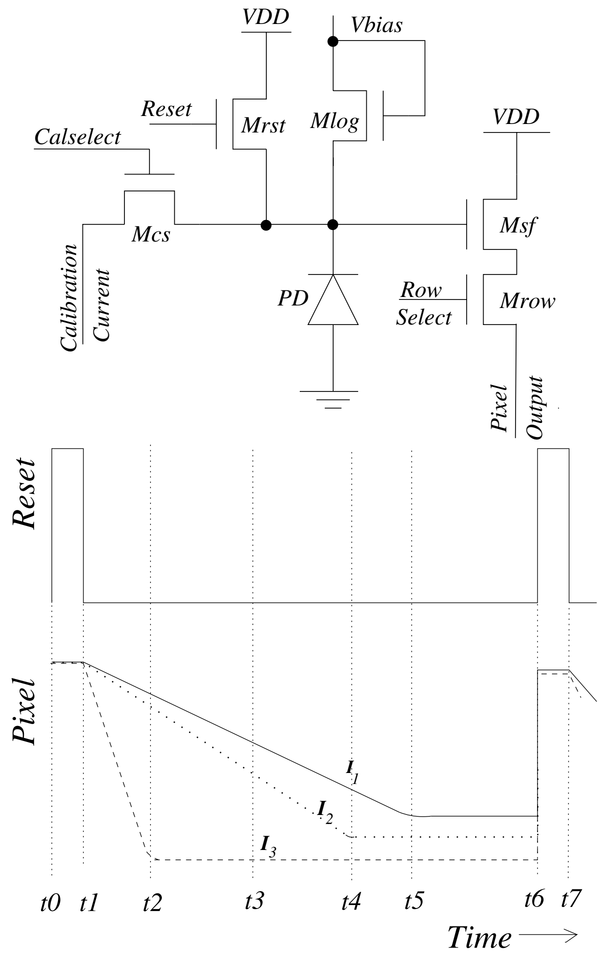

Fig. 1. a) A typical LLCMOS pixel b)The reset signal (Reset) and the corresponding LLCMOS pixel output at three different photocurrents

Figure 1 shows the pixel with a linear response at low light and logarithmic response at high light. By applying a positive pulse to the gate of the reset device, $Mrst$ between times $t0$

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and $t1$, the photodiode node can be reset to a voltage above the gate bias for the logarithmic load transistor, $Vbias$. This will turn off the logarithmic load device, $Mlog$. The photocurrent will then discharge the pixel capacitance to create a linear response. However, eventually the voltage in the pixel will fall below the gate bias voltage for the load transistor which will then supply current and an equilibrium will be achieved when the pixel output voltage is proportional to the logarithm of the photocurrent. If the pixel output voltage is measured at a predetermined time, for example $t4$, the pixel will have a linear response at low light-levels (e.g. I_1) and logarithmic response for high light-levels (e.g. I_3). The transition between the two regions is quick yet smooth. The pixel response has been modelled as a complex expression which breaks down to simple linear or logarithmic forms at low integration times/photocurrent or high integrations times/photocurrents, respectively [4]

$$\begin{aligned} V_{out} &= P' \log \left[\exp\left(\frac{V_{reset} - t_{int}(I_{ph} + I_{dr})Q'}{P'} \right) \right. \\ &+ \left. \frac{\{1 - \exp(-t_{int}(I_{ph} + I_{dr})Q'/P')\}\, R'}{(I_{ph} + I_{dr})} \right] \quad (1) \\ V_{out,lin} &= V_{reset} - t_{int}(I_{ph} + I_{dr})Q' \quad (2) \\ V_{out,log} &= P' \log R' + P' \log(I_{ph}) \quad (3) \end{aligned}$$

In these equations, I_{ph} is the photocurrent, I_{dr} is the leakage current flowing in the photodiode even in the absence of any optical stimulus. V_{reset} represents the pixel output at the time of reset. Q' represents the gain in linear region and is given by G_r/C, where G_r is the gain of the readout chain and C is the photodiode capacitance. P' represents the gain in the logarithmic region and is given by $G_r nkT/q$ (where terms have their usual meaning). R' is a complex term containing the offset as well as the gain in the logarithmic region and is given by

$$R' = 2I_{0,M1} \exp\left\{ \frac{G_r(V_{bias} - V_{T,M1}) + O_r}{P'} \right\} \quad (4)$$

Here, O_r is the offset added by the readout chain and other terms have their usual meanings. Variations in the parameters of this model can be used to characterise the fixed pattern noise in arrays of these pixels [4].

III. FIXED PATTERN NOISE CORRECTION BASED ON TRADITIONAL APPROACHES

The sources and the statistics of the fixed pattern noise for the LLCMOS in the linear region are similar to that of the linear active pixel sensor and hence double sampling techniques used in linear pixels could be used to remove the FPN in LLCMOS pixels as well [5]. Similarly, the FPN in the logarithmic region of the LLCMOS pixel has similar source and statistics as the FPN in typical logarithmic pixel arrays. This means that one would have to correct for the additive as well as multiplicative fixed pattern noise, as argued in [6].

A. Transition region

In the transition region, however, the pixel has a complex response and using either of the simpler models would lead to high errors [4]. Hence, the only way to correct for the fixed pattern noise in this region is to extract the photocurrent flowing in the pixel, using the complex model. Further, the non-linear response means that the extraction procedure has to be either an exhaustive search process or an iterative process. To perform an exhaustive search, one needs to compute the response of a pixel at every photocurrent and V_{reset} value (limited only by the required resolution and the noise of the system). This will lead to a very large matrix and hence, is not an efficient process.

An iterative process reducing the error between the predicted value and the actual value of the photocurrent is hence a preferred option. The algorithm shown in the box is an intelligent iterative approach to extract the photocurrent using a simple divide-by-2 scheme (binary search). The algorithm computes two currents assuming the pixel is operating in strict linear or logarithmic operation. The current producing lower error is used as one of the initial limits of the binary search algorithm. To identify the other limit, let us consider Figure 2, which shows the extracted currents assuming linear or logarithmic operation of the pixel. These currents $I1_{lin}$ and $I2_{log}$, will always be smaller than the actual current flowing in the pixel, $I1$ and $I2$. Further, the maximum transition region width measured from experiments is one decade and hence a higher limit of one decade away from the first current would encompass the whole transition region. Binary search is known to have complexity of $log_2 n$ and hence, it will converge within 10 iterations to an error below the model error in one decade of photocurrents.

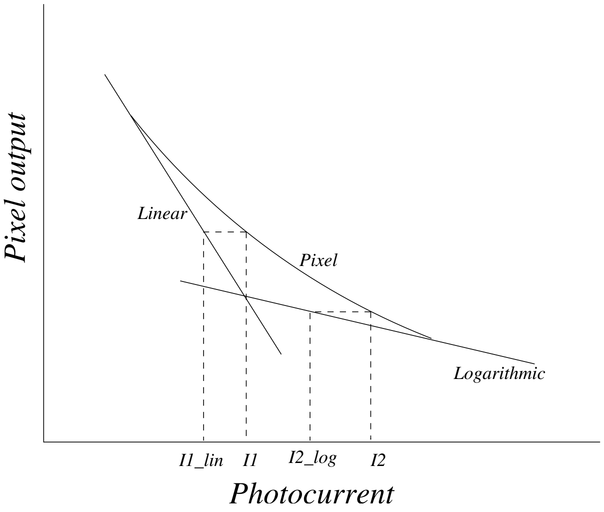

Fig. 2. Figure showing the currents extracted in transition region assuming linear or logarithmic operation are always less than the actual current.

Using the prescribed algorithm, currents have been extracted from simulation data. Figure 3 shows the absolute error in the extracted currents expressed as a percentage of the actual current. It is worth noting here that these absolute errors appear as systematic errors in the output of every pixel and hence do not affect the relative contrast in the image.

Algorithm - Intelligent Iterative Search

1) Compute the pixel parameters from simple parameter extraction procedure.
2) From the measured output and the reset levels, compute two photocurrents, which would have flown in the pixel, had it been completely linear or completely logarithmic region for these values.
3) Compute the response of the pixel using its full model and it's parameters at both of these currents.
4) Calculate the difference between these computed responses and the measured response of the pixel.
5) Use the current corresponding to lower error as the starting point of iterative computation.
6) Use a divide-by-2 and conquer algorithm (Binary search) with starting point and a current one decade higher than the starting points as two seeds. Compute the error at these two currents and recursively converge to the photocurrent within the error bounds. ⇒ END

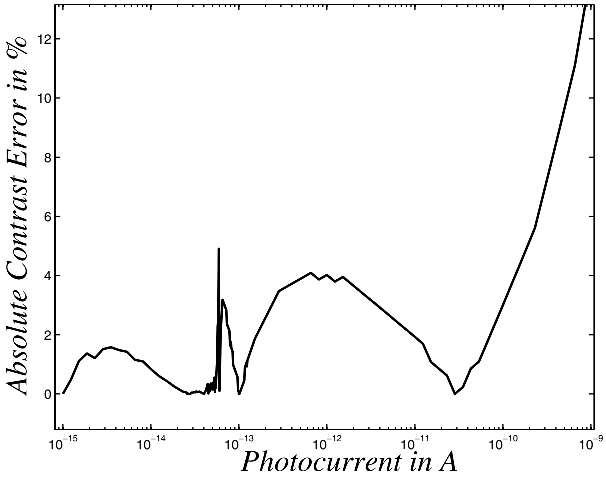

Fig. 3. Absolute error as expressed as percentage of the photocurrent when using the proposed photocurrent extraction routine.

B. Temporal Noise

The temporal noise needs to be removed before applying any FPN correction procedure in the image. The temporal noise sources in both linear as well logarithmic pixels have been extensively studied [7], [8]. The LLCMOS pixels are expected to suffer from the same sources. In the linear region, correlated double sampling can be used to remove the major source of noise while averaging over several frames can be used to remove the noise in the logarithmic region of operation.

A concern with averaging in transition region is that the net noise can move the pixel in different operating regimes in different frame, due to the very sharp transition region of the pixel. This means that the averaging process will be averaging different noise sources in different frames and hence a much larger number of frames would be required to produce good quality images. Temporal noise will also affect bounding limits of the divide-by-2 search algorithm. For some currents in Figure 2, the temporal noise in the pixel output may lead to a condition, wherein the extrapolated current producing lower error is higher than the actual current. Hence the divide-by-2 algorithm would never converge. With uncorrected temporal noise in the transition region, the errors from the photocurrent extraction procedure will increase. To study this effect, simulated data was used in the photocurrent extraction procedure with different amounts of Gaussian noise added to it. To remove the convergence errors due to temporal noise, the lower limit of binary search algorithm was placed at a current which was 20% lower than the extrapolated currents. Figure 4 shows the maximum error in the extracted photocurrent in the transition region. As discussed earlier, the error at zero noise is the model error and hence can be corrected systematically; however, the increasing errors at higher noise levels will introduce relative contrast error in the output image.

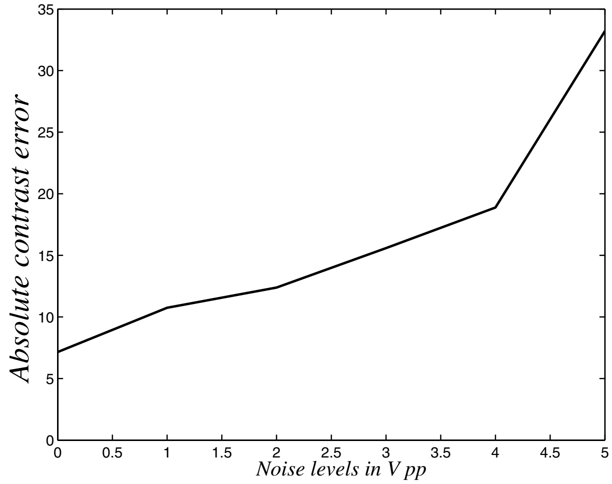

Fig. 4. The highest contrast error expressed as % of the photocurrent, when applying the photocurrent extraction procedure on simulated data with Gaussian noise

C. Experimental results of FPN correction

To test the validity of the proposed FPN correction procedure, the small array was stimulated with uniform images generated electronically using the calibration current source. On these images, double sampling was performed in the linear region, offset and gain correction in logarithmic region and iterative extraction was used in the transition region. To reduce the temporal noise, the data from 20 frames was averaged to reduce the final error below 2% of the photocurrent in the logarithmic region (close to the contrast limit of the human visual system).

The residual fixed pattern noise has been shown in Figure 5 as the relative contrast threshold of the imager at various currents. From these results, it is evident that good quality images with relative contrast threshold of less than 2% could be produced in either linear or logarithmic region in a LL-CMOS sensor. However, the transition region noise is high, on account of the temporal noise. To test if the high errors are indeed due to high temporal noise, the data in the transition region from one of the chips was averaged over 80 frames and the correction procedure was applied. The residual contrast threshold obtained was observed to be below 2%. Clearly, low FPN can be produced even in transition region; however, requirement of large number of frames means that this is an impractical technique for most commercial applications.

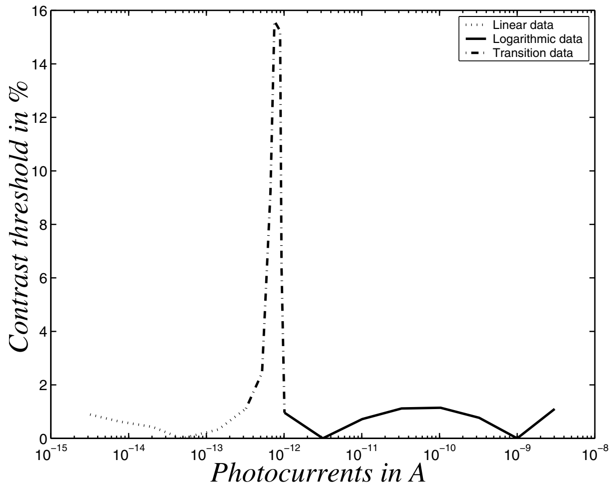

Fig. 5. Residual fixed pattern noise expressed as relative contrast threshold after the FPN correction strategy

IV. TWO READOUT TECHNIQUE

The unique non-linear response in the transition region of LLCMOS pixel is the principal reason of even an iterative routine failing to produce good quality image. One way to avoid the transition region could be to capture two outputs at different exposure times within the same frame. A high speed column parallel readout similar to the ones proposed by Mase and co-workers may be used for this purpose [9].

The pixel voltage after the longer exposure time may be used for all intensities, which have linear or logarithmic response after this integration time. Hard conservative thresholds may be used to determine the transition region. For the currents leading to the transition region response after this integration time, the pixel output captured after the smaller exposure time may be used. At this time, the pixel output for these currents will correspond to linear region of operation of the pixel. To better understand this, let us revisit the Figure 1(b). In this figure, if the time between $t1$ and $t4$ is used as the integration time for the frame, currents I_1 and I_3 produce linear and logarithmic response from the pixel respectively. However, the pixel is in transition region at the end of the integration time for current I_2. To remove the transition region effect, the pixel output is also measured during the integration period at a time $t3$. This output is used a measure for the photocurrent I_2. Since the pixel is still working in the linear region of operation, simple double sampling procedure could be sufficient to remove the fixed pattern noise. The frame time could be selected as an integral multiple of the smaller exposure time thereby having a simpler merging procedure for the output from sensor.

A double readout scheme has been simulated by using measured data from an array. Each pixel was monitored throughout its integration time. Hence, pixel output was available for any integration time. From this data, the two integration times were selected. The smaller integration time, was half of the larger and was used only for the currents, which would lead to the transition region operation. With this setup, the residual fixed pattern noise was found to be less than 2% for the entire useful dynamic range.

V. CONCLUSION

Pixels with linear response at low light and logarithmic response at high light are able to capture the wide dynamic range available in nature without the dark current related effects observed in logarithmic pixels. Correlated double sampling and two-parameter correction procedures are able to correct the fixed pattern noise in an image produced by these images in linear and logarithmic regions, respectively. In the transition region, an iterative algorithm could be used to correct for the fixed pattern noise. However, high temporal noise leads to disapointing results. A technique using two readings during the same exposure has been proposed which is capable of removing the effects associated with the complex transition region. Future work will concentrate on practical realisation of this technique.

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