High Dynamic Range Imaging using Combined Linear-Logarithmic Responses from a CMOS Image Sensor.

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Abstract

Dynamic range is an important parameter of an image sensor. This paper describes the processes required to produce a high dynamic range image by combining the linear and logarithmic data from a CMOS image sensor. The process is to be implemented in a real-time imaging system without the use of memory in which to store intermediate images. It must therefore be possible to calibrate the logarithmic data and combine it with the linear in the readout chain. Such a sensor has been designed and details of its operation are presented.

1. Background

The majority of commercially available CMOS and CCD sensors have a limited dynamic range that can be exploited by everyday scenes. Pointing a video camera out of a window will normally render the indoor or outdoor part of the image useless. Much comparison is made to human vision which posseses an interscene dynamic range in excess 200dB and an intrascene range of around 80dB [1]. Machine vision applications can often require an imaging solution with intrascene dynamic range performance greater than human vision.

Linear integration is the most common mode of operation found in today's CMOS image sensors. However, whilst providing the best performance at low light levels their ability to image scenes of a high dynamic range is often insufficient. Alternatively, logarithmic sensors are well known to exhibit a high dynamic range but suffer from low sensitivity and increased Fixed Pattern Noise (FPN). Linear integrating and continuous time logarithmic CMOS image sensors are not new systems in themselves with much work being done on each system independently but little together. A combined linear logarithmic response arrangement has been presented in [2] however, no information is given about how to deal with FPN which is major drawback of logarithmic response pixels.

This paper demonstrates how dynamic range can be extended from the combination of a linear and logarithmic image. Figure 1 shows an image taken with a conventional integrating CMOS image sensor. The rightmost facade displaying the University Crest and company logo is overexposed causing the text round the crest to be unreadable. In the shadows on the left side of the scene the facade and cartoon toy require the long linear exposure for their lower illumination. A decrease in integration would lose the detail captured in the shadows on the left.

A conventional logarithmic arrangement is shown in Figure 2. The photocurrent flows through the load device (M2) and sets up a gate-source voltage (Vgs) that varies logarithmically with the photocurrent. The value of Vgs will vary between zero and the threshold voltage but as Vgs nears the threshold voltage the region of operation moves from weak-inversion to strong inversion ending the logarithmic dependence on the current. Vgs will vary by around 60mV per decade of light intensity thus is able to work across a range of 6 decades (120dB). Such a pixel suffers from a low Signal to Noise Ratio (SNR), lag and FPN. FPN comes mainly from the threshold voltage variation of the source follower (M1) and the load device and is a major disadvantage of a logarithmic imager. Attempting to correct this variation can be done by storing each pixels offset in a framestore and adjusting the pixel data as it is read out. The overhead in memory space is undesirable thus so called 'on-chip' methods of calibration have been explored [3][4]. Such schemes will work well if the FPN is simply an offset but it has been reported that gain errors also contribute to the FPN [5].

2. Logarithmic Calibration

Ideally, under uniform illumination conditions the output from each pixel in the array would be at the same level. Unfortunately, due to process variation a raw logarithmic image (Figure 3) suffers from FPN amounting to 100% of a decade of light intensity.

Joseph and Collins [5] discuss the correction of FPN by applying a simple offset, offset and gain or offset, gain and bias. The offset gain and bias correction cannot be solved analytically and requires iteration to find a solution. Only the first two means of calibration are examined here as the last does not lend itself well to a real-time system. The model used for the two parameter correction is detailed below for clarity.

The response of a j^{th} pixel is modelled by $\hat{y}_{ij}$ and is given by Equation 1 in which offset a_j and gain b_j vary spatially to an illuminance x_i. c is assumed to be constant.

$$\hat{y}_{ij} = a_j + b_j \ln(c + x_i) \quad (1)$$

The parameters are found by minimising the Mean Squared Error (MSE) after assuming correction should move the response of individual pixel values toward the array average (for flat const illumination image). Correction is applied on a per-pixel basis and is given by:

$$y'_j = \frac{y_j - a'_j}{b'_j} \quad (2)$$

where:

$$a'_j = \bar{y}_j - b'_j \bar{y} \quad (3)$$

$$b'_j = \frac{\sum_{i=1}^{M} (y_{ij} - \bar{y}_j)(\bar{y}_i - \bar{y})}{\sum_{i=1}^{M} (\bar{y}_i - \bar{y})} \quad (4)$$

with parameters:

- Average per pixel over the intensity range

$$\bar{y}_j = \frac{1}{M} \sum_{i=1}^{M} y_{ij} \quad (5)$$

- Average of the pixel array at intensity i

$$\bar{y}_i = \frac{1}{N} \sum_{j=1}^{N} y_{ij} \quad (6)$$

- Average over the intensity range of the pixel array averages

$$\bar{y} = \frac{1}{M} \sum_{i=1}^{M} \bar{y}_i \quad (7)$$

Joseph and Collins use 24 images (M=24) to perform the calibration but this is not implementable in a real-time system without using a frame store. This paper provides results of calibration with M=2 which represents the minimum number of reference frames required to perform a two parameter calibration.

The effectiveness of the calibration is measured by monitoring the remaining variation across an image of uniform illumination. The standard deviation is expressed as a percentage of the light intensity per decade which is a common figure used for comparison. The reference images have been averaged to remove kTC noise. The CMOS sensor used to capture the images was a conventional 3T APS fabricated in a 0.35μm process. The reset line (gate voltage of M2 from Figure 2) was held at Vrt to enable logarithmic operation.

Table 1 shows the results of simple offset calibration in which the difference between two frames is calculated on a per-pixel basis. A '*' signifies the frames used to perform the calibration.

Frame						St. Dev as % of a decade
f1	f2	f3	f4	f5	f6	
*		*				2.47
*			*			2.86
*				*		4.21
*					*	4.81

f1 = 885mW/m^2 f4 = 200mW/m^2
f2 = 726mW/m^2 f5 = 3.6mW/m^2
f3 = 496mW/m^2 f6 = 0.8mW/m^2

Table 1: Simple offset calibration

It can be seen that the remaining FPN reduces as the two reference frames used move closer together. Variation in the sub-threshold slope factor of the device from which the logarithmic reading is taken means that reference points far away from the actual operating point show a gain error as well as an offset. The FPN from the constant illumination images can be substantially reduced if the reference frame is close to the actual illuminance. However, in a high dynamic range scene it will not be possible for the reference point to be close to all the pixel values thus the reduction of FPN will be less. The three decades of illumination in Table 1 represents a maximum calibration distance if the dynamic range in logarithmic mode is 6 decades of light.

Table 2 shows the results from the offset and gain calibration in which a straight line is fitted between the reference frames (given by a '*') for each pixel. 'cal' signifies the frame that was corrected.

Frame						St. Dev as % of a decade
f1	f2	f3	f4	f5	f6	
*	cal				*	1.59
*		cal			*	2.34
*			cal		*	2.35
*				cal	*	2.3
*	*	cal	*	*	*	1.98
*	*	*	*	cal	*	2.2
*		*		cal		28
f1 = 885mW/m^2			f4 = 200mW/m^2			
f2 = 726mW/m^2			f5 = 3.6mW/m^2			
f3 = 496mW/m^2			f6 = 0.8mW/m^2			

Table 2: Offset and gain calibration

Table 2 shows that two parameter calibration using only two reference frames gives a flatter response of FPN reduction across illumination compared to the simple offset calibration. Furthermore, the improvement achieved when more than two reference frames are used is not significant. These results are comparable to that achieved by Loose in [4] but should still be reproducable if the process has more severe slope variations. The last line in Table 2 shows the results of a calibration when the two reference frames are at a higher illumination than the image to be corrected. Similar results are obtained if both reference frames are at a lower illumination level than the frame to be corrected. The remaining FPN is extremely high and would be very noticable in a real image. Thus, when two parameter calibration is perfomed the reference points chosen must be either side of the actual operating point to achieve good FPN reduction. This dictates the range that the 'on-chip' calibration scheme should work over. Figure 4 shows the raw image of Figure 3 after two parameter calibration with only two reference frames.

Illuminating the device as a means of calibration is not practical in a real time imager thus calibration is performed by pulling a reference current through the load device. If the reference current is matched across the array the FPN will be the same as it would be were it uniformly illuminated. The offset and gain calibration algorithm of Equation 2 can be implemented without a frame memory if each pixel is read three times (two reference levels and the actual value).

3. Image Fusion

By adjusting the reset voltage applied to the pixel (gate voltage of device M2, Figure 2) and changing the timing so it is pulsed or continuously on, it is possible to operate the conventional integrating sensor in both linear and logarithmic modes. A high dynamic range scene was captured in linear and logarithmic modes by this method. The linear scene is shown in Figure 1. The above calibration technique was used to reduce the FPN of the raw logarithmic image and produce Figure 3. Figures 1 and 3 were then combined by substituting logarithmic data for any linear pixels that held a value in excess of a given threshold. The threshold value was chosen such that logarithmic data was substituted where the linear data began to saturate. Figure 5 shows the areas (blackened) where logarithmic data is to be substituted. The algorithm used to fuse the two images is given below and shown graphically in Figure 7:

- The linear image was parsed to find the value nearest to the threshold. The location(s) of these pixels were stored.
- The values at the corresponding locations in the logarithmic image were then averaged.
- The difference between the threshold (or nearest found value) and the average of the logarithmic pixels was calculated and became the offset.
- All pixels in the linear image greater than the threshold (or nearest value) were replaced by the logarithmic equivalent value plus the calculated offset.

The resulting image suffered from poor contrast in the areas where pixels had been replaced. This is due to the relatively low sensitivity of the logarithmic sensor to light. By applying a gain to the logarithmic pixels, the contrast of the replaced pixels improved. The down side is a reduction in the contrast of the linear section but this is a limitation of the display not the image processing. The combined linear logarithmic image is shown in Figure 6.

To implement in a real system it will obviously not be possible to examine each linear frame and look for the linear pixels close to saturation. Initially, the offset will take one frame to be calculated and can then be applied to future frames. Unfortunately, every time the linear integration period is altered a new offset needs to be calculated so that the logarithmic data is correctly mapped to the linear.

4. Sensor implementation

Figure 8 shows the new pixel arrangement for logarithmic mode. An amplifier has been added to improve the settling time. The node 'pix' will now be held at the reference voltage, Vref, and the logarithmic voltage will appear on the output of the amplifier. The offset of the amplifier, voff, will vary from pixel to pixel but will be removed during the calibration process. Also shown is access transistor (M4), through which the calibration current can be drawn, isolate transistor (M5), which prevents the photocurrent corrupting the calibration process, and anti-bloom device (M7), which can direct excess photocurrent to Vrt. To keep the pixel size as small as possible the amplifier is common to all pixels of the same column. The source follower from Figure 2 becomes the inverting input and is the only part of the amplifier to be situated in the pixel. The pixel achieves a pitch of 5.6μm with a fill factor of 33% in a 0.18μm single poly, four layer metal technology.

The full pixel displaying all devices is shown in Figure 9. cal/reset and isolate are raised to reset pix and the photodiode to a voltage set in col4. Simultaneously the gate of M2 is pre-charged low via col3 to prevent it interfering with the integration. After the set exposure the source follower consisting of M1 and M3 is used to read out the pixel value (col2 set to Vrt and a current source connected to col1). Double sampling can be performed to remove the threshold variations in the source follower. The amplifier is then connected round the pixel and the logarithmic readings can be taken. The sensor designed employs a column parallel architecture with a single slope ADC and two SRAM banks per column. Two parameter calibration of the logarithmic result is processed in the readout chain in the digital domain thus requires 4 ADC cycles per line time(linear, log , log ref1, log ref2). If simple offset calibration is used to correct the logarithmic result only 2 ADC cycles are required due to the differential input of the ADC.

It was stated earlier that two parameter calibration requires a reference point below and above the logarithmic operating point. Pulling a reference current through M2 via access transistor M4 is effective if the calibration current can be made sufficiently high to give a short settling time. The associated capacitance of the column prevents the use of all but high calibration currents. For this reason a novel method of generating a reference current has been introduced that is directly applicable to this logarithmic arrangement. The equation $I = C\frac{\delta v}{\delta t}$ states that a constant current will result if a fixed capacitance is subjected to a constant change in voltage. This phenomenon can be applied to the circuit of Figure 8 to pull a reference current through device M2. Devices M4 and M5 are turned OFF then a linearly ramped voltage is applied to the non-inverting terminal of the amplifier. pix will track the non-inverting terminal thus creating a constant change in voltage across the capacitance on node pix. The generated current will have to be supplied by M2. The same current can be generated in each pixel if the capacitance on pix is well matched across the array. By changing the slope of the voltage ramp applied to the non-inverting terminal the reference current can be programmed.

5. Conclusion

This paper has shown that reduction of FPN is possible with an improved calibration scheme that is reproducible in a real-time system without incurring the overhead of a framestore memory block. In addition a means of producing high dynamic range images has been investigated using actual data and was found to recover lost information from a linear image where sections have saturated. A CMOS imager that produces frames containing both linear and logarithmic data has been designed and submitted for fabrication. This has been made possible by a logarithmic arrangement that reduces lag and a novel calibration scheme.

6. Acknowledgements

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Figure 1: Linear image with insufficient dynamic range

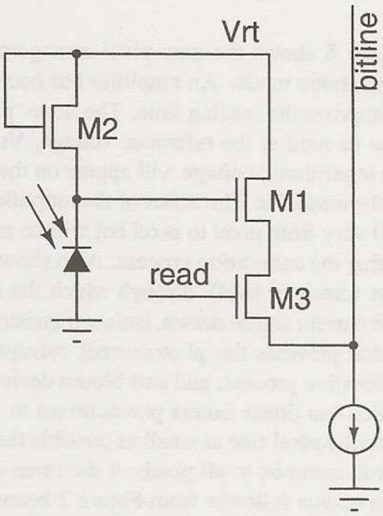

Figure 2: Conventional logarithmic architecture

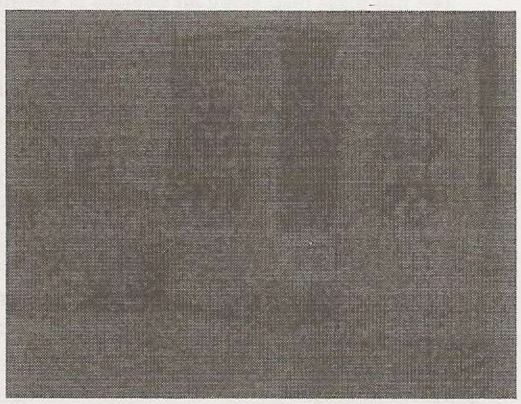

Figure 3: Raw Log image

Figure 4: Calibrated Log image

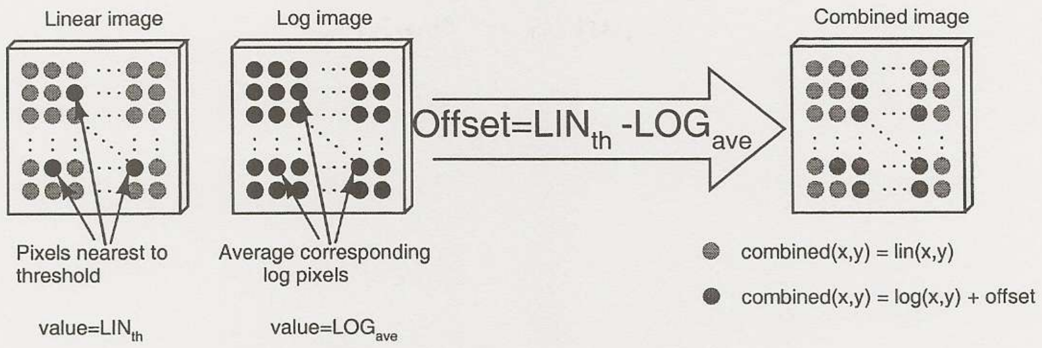

Figure 7: Log substitution.

Figure 5: Linear image with substitution areas in black.

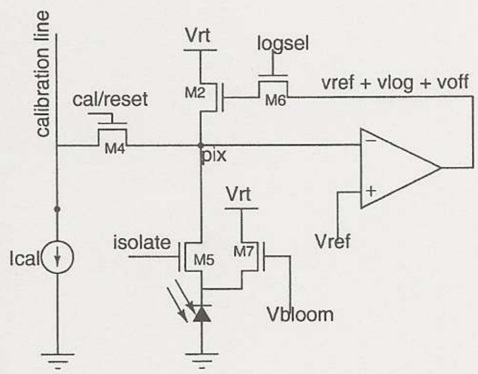

Figure 8: New logarithmic Pixel.

Figure 6: Combined Linear Logarithmic image.

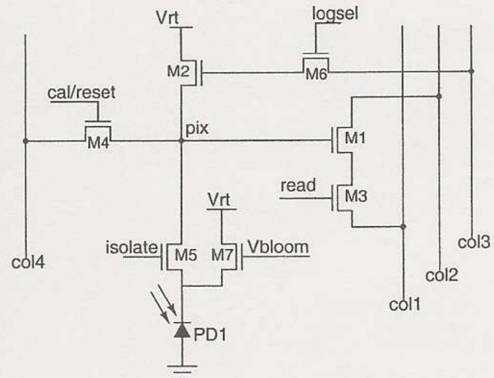

Figure 9: Full pixel.