High Performance CMOS Logarithmic Sensor with Continuous Adaptive FPN Correction

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ABSTRACT

This paper presents a CMOS logarithmic sensor based on specially designed 4T charge mode Lin-Log pixel, readout and associated signal processing. Each pixel generates 2 different parameterized captures. These capture parameters can be either exposure time or FWC of the pinned photodiode. A unified precise logarithmic response is generated from these captures by simple pixel-wise image processing. This processing can be implemented as background continuous adaptation process which can overcome the environment dependence of pixels. A prototype sensor based on exposure time mixture has been designed and fabricated in a standard CMOS process. The associated image processing has been implemented on PC. The firsthand results demonstrate a high sensitivity, native instant ultra-wide dynamic range and low FPN.

Introduction

Logarithmic image sensors have the advantages of ultra-wide instant dynamic range, light invariant local contrast sensitivity and easy color imaging. The grayscale of a logarithmic image is indexed to the reflectance map of a scene which is locally independent of ambient light and its change. The logarithmic compression gives a huge dynamic range without any ISP for vision oriented applications.

These characteristics make it an ideal image sensing device for artificial vision applications such as autonomous driving, mobile robot, drone navigation, etc. The development of logarithmic pixels is easy and has passed the following evolution:

1) pixel based on linear-logarithmic conversion in diode or subthreshold MOSFET[1,2,3,4]. Despite simplicity, this solution has a lot of drawbacks such as large fixed pattern noise, image lag, high noise, large pixel size and fatal temperature dependence.

2) pixel using photodiode as a solar cell[5,6]. Its open-circuit voltage provides a precise logarithmic response. Since the dark response of a solar cell is zero, an on-chip FPN compensation can be done by resetting the photodiode to the ground. This reset also removes the image lag. This solution has found limited industrial applications, but it suffers from the following drawbacks such as low QE, large pixel size and large readout noise due to KTC noise. Incorporation of solar cell mode photodiode in charge mode 4T pixel has been tried without much success because a strong substrate anti-blooming is needed which reduces QE to an unacceptable level[8].

3) pixel using Lin-Log response[7]. The Lin-Log response can be obtained in both 3T and 4T pixels. In a 4T pixel, it can be obtained from PPD overflow, TX gate overflow or specific overflow gate/doping. At low light level, it works like a classic linear pixel with all the advantages of charge mode pixel such as high QE, low readout noise. At high light level the transition to logarithmic response gives instant wide dynamic range. The Lin-Log transition point depends strongly on process dispersion and temperature.

Since all the cited advantages for artificial visions of a logarithmic sensing are valid only with a whole-range pure logarithmic response. Previous solutions can not satisfy this criterion even with many proposed correction schemes[9,10]. Here we propose a patented hardware-software combined method which can generate a precise and FPN compensated logarithmic image from a specially engineered Lin-Log sensor.

Working Principle

The basic idea is illustrated in Fig. 1, the long exposure response (RL) makes the Lin-Log transition sooner than the short exposure one (RS). By comparing the responses RL and RS, 3 regions can be determined: Lin-Lin, Log-Lin and Log-Log. Pixel's instant operating region can be determined by the ratio between RL and RS.

It has been proved from measurement that pixel's linear response has very low FPN and pixel's logarithmic slope is quite uniform. From this observation, we can transform

RS response to its logarithm and then merge it with RL after subtracting an offset OS. The value of OS can be determined when pixel is operating in Log-Lin region, since K*Log(RS) is FPN free (K is the logarithmic slope which can be measured and corrected according to operation temperature). By comparing K*Log(RS) and RL, the value of OS can be fixed. Then a simple fusion by using MAX(K*Log(RS), RL-OS) gives an FPN corrected pure logarithmic response. A continuous computation routine can be implemented either on-chip in the sensor or inside application processor to update the value of OS continuously each time when the pixel's responses are in Log-Lin region. This continuous adaptive routine can overcome the OS drift due to environmental parameters such as temperature, power supply or circuit component aging, etc.

Prototype CMOS Sensor & Camera System

An experimental CMOS sensor has been designed and fabricated by using a pure digital 180nm CMOS process with several optional ion implantations for the pixel. Fig. 2 illustrates the overall architecture of this sensor. The Lin-Log function is created by using controlled TX leakage. The low voltage of TX control level can be adjusted to adjust the Lin-Log transition point. The long and the short exposure times are set by splitting the frame time through a classic electronic rolling shutter.

The prototype sensor is connected to a PC via an USB3 interface. All the control signals are generated by FPGA. A Windows based software captures the dual frame images and applies the necessary image processing and display. Raw data have been used for characterization. Tab. 1 gives the technical summary of this protype sensor. The residual FPN is measured at ~2% of contrast which could be still improved by optimizing the fusion process.

Discussion and further improvements

The correction procedure has been implemented by software on PC. The continuous FPN compensation has been validated with success. But we have observed that the sharp motion edges trigger OS errors due to the optical intensity transition between 2 frames, especially when this transition is from high to low. Additional criterion based on the spatial information of the output image should be taken into consideration. Also at low light level, the SNR in short exposure response is bad and an improvement can be done by merging short and long responses at low light level.

Conclusion

This paper presents a CMOS logarithmic sensor with high sensitivity and small pixel size. The full range precise logarithmic response has been obtained by a hardware-software mixed approach. The troublesome Lin-Log transition dispersion has been overcome by processing responses from long and short exposure times. This processing can be implemented as a continuous adaptation background task which can be done either by on-chip hardware or by firmware on application processors. This sensor is particularly suited to AI based artificial intelligence systems such as automatic driving, robots, drones, etc.

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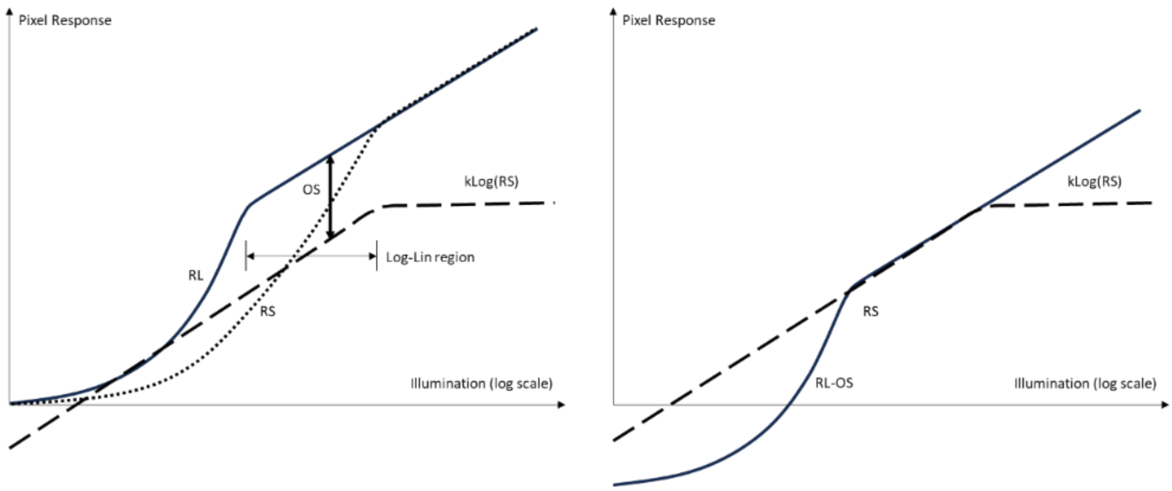

Figure 1. Principle of the proposed continuous adaptive FPN correction and pure logarithmic response generation.

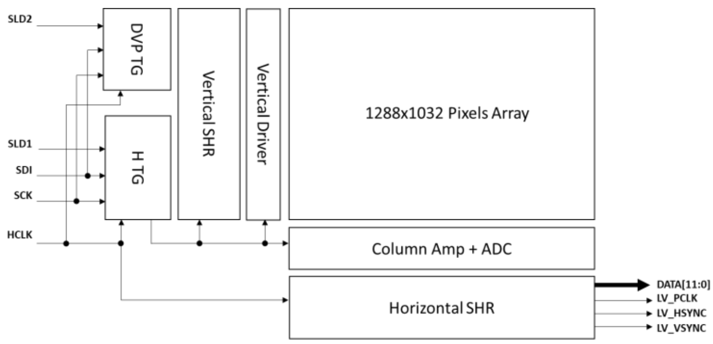

Figure 2. Overall architecture of the prototype sensor.

Parameter	Value	Unit	
Pixel Size	5	um	No microlens, FF=44%
Pixel Type	4T with Lin-Log response		Lin-Log transition by TX voltage
CMOS Process	180nm CMOS + options		
Resolution	1288 x 1032	pixel	8 dummy pixels
Readout method	Staggered dual readouts		Rolling shutter
ADC resolution	12	bit	
ADC conversion range	750	mV	
Readout Noise	1.5	electrons	With x8 column gain and without dark current contribution
Logarithmic slope	214	LSB/decade	At room temperature
Raw Logarithmic FPN	45	LSB	
Residual FPN	~ 4	LSB	Corresponding to 2% contrast ratio
Image Readout Speed	80	Mp/s	60FPS single frame and 30FPS dual frame
Power consumption	150	mW	

Table 1. Main technical characteristics of the prototype Logarithmic sensor.

Figure 3. Sample images from the prototype sensor. The local contrast stability of a precise logarithmic law sensor is clearly demonstrated by edge extraction on these images.