Digital calibration technique for highly linear wide dynamic range CMOS imaging sensor

J. Yuan, H.Y. Chan, S.W. Fung and B. Liu

A novel digital calibration scheme is developed to improve the linearity of a wide dynamic range (DR) CMOS imaging sensor, with a low calibration overhead. Experimental results show that the distortion of the fabricated imaging sensor reaches −75.6 dB over the 95.3 dB DR after calibration.

Introduction: The dynamic range (DR) of CMOS imaging sensors is limited by the voltage space at the integration node. The DR can be non-linearly expanded by scaling the integration time or the integration capacitance [1]. However, the imaging sensor’s linearity is low from these wide DR schemes. Biomedical and scientific applications require imaging with high linearity [2]. The self-resetting pixel as shown in Fig. 1 can linearly expand the DR. The pixel resets itself after calibration. The number of overflows (Dw) is recorded by a counter. The residual voltage (Vr) at the end of the integration is quantised by a column analogue-to-digital converter (ADC). If the comparator is ideal, the accumulated photo voltage can be readily calculated by

\[ V_{\text{ph}} = D_w V_r + D_w \text{LSB}_0 \]  

where \( D_w \) is the digitised residual voltage. \( \text{LSB}_0 \) is the least significant bit size of the column ADC. The problem of the self-resetting pixel is that \( V_r \) is nonlinearly dependant on the photo current \( (I_{\text{ph}}) \) owing to the offset and delay of the low-power in-pixel comparator. This is the main reason that previous schemes with an in-pixel comparator all achieve low linearity [3, 4].

![Fig. 1 Self-resetting pixel, and ideal dynamics of pixel](image)

a) Self-resetting pixel  
b) Ideal dynamics of pixel

In the work reported in this Letter, we developed a digital calibration scheme to compensate the \( V_r \) nonlinearity of a modified self-resetting pixel as shown in Fig. 2a so that very high linearity can be achieved over the wide DR. The detailed calibration procedure with mathematical derivation is reported in this Letter. The modified self-resetting pixel in Fig. 2a, a set of on-chip calibration currents \( (I_{cal}) \) and a 16-bit on-chip current reference ADC (CRDAC). The digital calibration procedure needs two quantisers. The pixel digitises a pixel current \( (I_{\text{ph}}) \) into \( D_s \) and \( D_r \), so that

\[ I_{\text{ph}} = D_s I_{\text{ph}} + D_r I_{\text{ph}} + \Delta I_r \quad |\Delta I_r| < 0.5 I_{\text{ph}} \]  

where \( I_{\text{ph}} \) is the unit current. \( I_{\text{ph}} \) is the LSB of the current unit. \( \Delta I_r \) is the quantisation error of the column ADC. The reference ADC digitises the calibration current \( I_{\text{cal}} \) into \( D_s \), so that

\[ I_{\text{cal}} = D_s I_{\text{cal}} + \Delta I_s \quad |\Delta I_s| < 0.5 I_{\text{cal}} \]  

where \( I_{\text{cal}} \) is the least-significant-bit size of the reference ADC. \( \Delta I_s \) is its quantisation error. The calibration procedure runs in two modes.

1. Calibration mode (\( D_{s,0} \)): The procedure starts by measuring the \( \text{LSB}_0 \) of the column ADC using the reference ADC. The maximal calibration current which does not trigger an overflow \( (I_{\text{cal},0}) \) is injected into the pixel. If the pixel digitised value is \( I_{s,0} \), the reference ADC digitised value is \( D_{s,0} \), then

\[ I_{s,0} = D_{s,0} I_{\text{ph}} + \Delta I_r \quad |\Delta I_r| < 0.5 I_{\text{ph}} \]  

\[ I_{s,0} = D_{s,0} I_{\text{cal}} + \Delta I_s \quad |\Delta I_s| < 0.5 I_{\text{cal}} \]  

The column ADC LSB is then

\[ I_0 = D_{s,0} I_{\text{ph}} - \frac{1}{D_{s,0}} |\Delta I_r + \Delta I_s| \]  

\( N_c \) calibration currents are injected into the pixel successively to sample the \( V_r \) function. For each \( I_{s,i} \), if the pixel digitised values are \( D_{s,i} \) and \( D_{r,j} \), and the reference ADC digitised value is \( I_{s,i} \), it can be derived from (1), (3), and (6) that the potential well size \( (I_{\text{cal}}) \) can be digitally estimated as

\[ D_{s,i} = \frac{1}{D_{s,0}} \left( D_{s,0} I_{\text{cal}} + D_{r,i} \right) \]  

The error between \( I_{s,i} \) and its digitised value \( D_{s,i} \) is

\[ \Delta I_{s,i} = \frac{1}{D_{s,0}} \left( I_{s,i} - \frac{1}{D_{s,0}} |\Delta I_r + \Delta I_s| \right) \]  

\( I_{0} \) and \( I_{s,i} \) are close in the designed imaging sensor, so the estimation error of \( I_{s,i} \) is less than \( 2 I_{\text{ph}} \). Therefore, the digital calibration procedure degrades about 2 bit resolution compared to the reference ADC owing to the quantisation error. The \( N_c \) samples \( \{D_{s,i}, D_{s,0}, \ldots, D_{s,i} \} \) on the \( V_r \) function are used to interpolate the rest of the nonlinear function.

2. Normal mode: For an incident photocurrent, the digital potential well \( D_{s,0} \) can be interpolated from the sampled \( V_r \) function as

\[ D_{s,0} = D_{s,0} + S_s (D_{\text{ph}} - D_{s,0}) \]  

where \( D_{\text{ph}} \) is the digital photocurrent. \( S_s \) is the slope of the interpolation segment which contains \( D_{\text{ph}} \) as shown in Fig. 2b. \( (D_{s,0}, D_{s,i}) \) is the starting sample of the interpolation segment. With the potential well size, the photocurrent can be calculated by the pixel quantisation results:

\[ D_{\text{ph}} = \frac{D_{s,0} (D_{s,0} - S_s D_{s,0}) + D_{s,0} D_{s,0}}{1 - S_s D_{\text{ph}}} \]  

From (9) and (10), the digital photocurrent can be calculated as

\[ D_{\text{ph}} = \frac{D_{s,0} (D_{s,0} - S_s D_{s,0}) + D_{s,0} D_{s,0}}{1 - S_s D_{\text{ph}}} \]  

For the designed pixel, the interpolation segment \( x \) can be easily determined by \( D_{\text{ph}} \) estimated using the uniform \( D_{s,0} \) as the pixel nonlinearity is not severe.

Decoder structure: The calibration and recovery procedures are implemented by two decoders in an off-chip digital signal processor (DSP). Fig. 3 shows structures of the decoders. The rectangular boxes are memory elements. Signals outside boxes are inputs or outputs to the DSP.
The decoder in Fig. 3a calculates the interpolation parameters in the calibration mode. The speed of this decoder is not critical. The decoder in Fig. 3b recovers the photocurrent during normal operation. It supports the real-time calculation. As the reference ADC quantises currents into 16 bits, $4V_a - 2$ bytes memory is required for each pixel. For a 1K-pixel image sensor, $4V_a - 2$ KB memory is needed in the DSP. If the pixels in the imaging sensor are processed in serial, the decoder needs to run at the rate $f_{frame} \times N_r \times N_c$ Hz, where $N_r$ and $N_c$ are the imager row and column numbers. The hardware overhead for the digital calibration is low.

**Measurement results:** A proof-of-concept $32 \times 32$ imaging sensor is fabricated in a 0.35 μm 2P4M CMOS process. The measured dynamic range of the imaging sensor is 95.3 dB.

The pixel linearity is measured by 17 currents. Without calibration, a uniform $V_a$ is used to estimate the accumulated photo voltage $D_{ph}$. The spectrum of the recovered photo voltages is plotted in Fig. 4a. The harmonic distortion is −36.4 dB.

With the reference ADC, the digital calibration procedure is performed on pixels of the imaging sensor, with an off-chip DSP. $V_a$ of one pixel is sampled by 11 $I_{cal}$ currents. The sampled nonlinear function is used to recover the accurate photocurrent. The spectrum of the recovered photo voltages after calibration is shown in Fig. 4b. The harmonic distortion is improved to −75.6 dB.

**Conclusion:** A digital calibration scheme for a wide dynamic range CMOS imaging sensor is introduced. The calibration scheme compensates the nonlinearity of a self-resetting pixel in the digital back-end, with low overhead. The mathematical derivation of the digital calibration procedure shows that the digital calibration will lose 2 bit resolution than the reference ADC owing to the quantisation error. With the scheme, the CMOS imaging sensor can achieve −75.6 dB distortion over 95.3 dB dynamic range. The digital calibration scheme can also effectively remove the fixed-pattern noise. The WDR imaging sensor with the digital calibration scheme provides a good solution for biomedical diagnostics.

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