

A Novel Adaptive Logarithmic Digital Pixel Sensor

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Abstract—A major problem associated with complementary metal–oxide–semiconductor and charge couple device imagers is their limited dynamic range (DR), typically 60–70 dB. This falls far short of covering the wide illumination ranges found in natural scenes (typically 120–140 dB). Biological retinas are known to feature adaptive, logarithmic-type responses enabling them to cover a very wide DR, without compromising the resolution. This letter presents a novel way to realize such an adaptive logarithmic response by combining a digital time domain vision sensor and a simple adaptive digital quantizer. This letter presents the theory and experimental results for an adaptive logarithmic response sensor featuring over 100-dB DR.

Index Terms—Adaptive logarithmic pixel, complementary metal–oxide–semiconductor (CMOS) image sensors, digital pixel sensor (DPS).

I. INTRODUCTION

TYPICALLY, a vision sensor encodes illumination intensity into a voltage, a current, or timing information. Imaging wide dynamic range (DR) natural scenes remains a major challenge for solid-state image sensors. Most voltage and current mode image sensors exhibit a saturating linear response, with a DR, typically limited to 60–70 dB [1]. However, light reflected by natural scenes spans over 140-dB DR: from 0.001 lux at night and up to 10 000 lux in bright sunlight [2].

To meet such a challenging requirement, a pixel with a logarithmic response has been developed and widely used over the last decade [3]. Unlike a linear-response pixel (the norm for charge couple device or complementary metal–oxide–semiconductor (CMOS) sensors), which integrates the charge produced by photon absorption over a fixed time, a logarithmic pixel continuously converts incident photons into a voltage that is proportional to the logarithm of the light intensity, which permits a range of operation of over five decades of illumination. This is achieved by exploiting the logarithmic current–voltage relationship of an MOS transistor operating in the weak inversion region. While this provides signal compression at the pixel level, it loses the benefit of integrating the small photocurrent over time, resulting in low voltage swing (0.2–0.3 V), poor resolution, low signal-to-noise ratio, and challenging back-end analog-to-digital converter (ADC) design. In fact, a logarithmic pixel trades DR for lower resolution as a large input range is encoded into a limited voltage swing.

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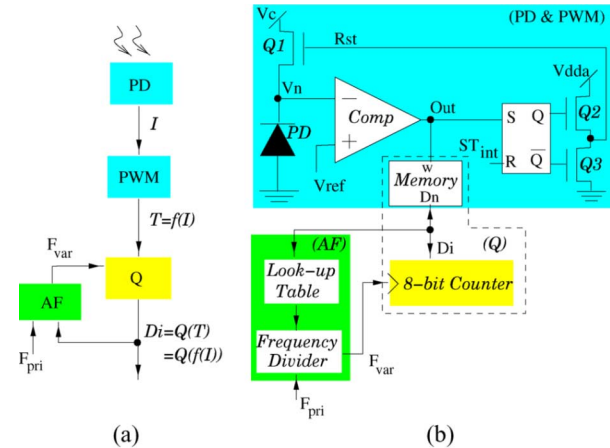


Fig. 1. (a) Adaptive logarithmic DPS sensor concept. Here I , f , Q , AF , and D_i refer to the photocurrent, the PWM transfer function, the quantizer, the adaptive feedback, and the digital output, respectively. (b) Block diagram of the logarithmic DPS sensor, showing a single pixel and the quantizer. (Color version available online at <http://ieeexplore.ieee.org>.)

It is fascinating to observe how biological photoreceptors simultaneously deal with a large DR, while maintaining high resolution [4]. It has been reported that typical cone photoreceptors have a larger response to changes in illumination than to steady-state illumination [4]. This feature cannot be delivered by a logarithmic sensor as the logarithmic transfer function is set by the characteristics of the pixel level transistors.

Inspired by this fascinating biological feature, we propose in this letter an adaptive logarithmic digital pixel sensor (DPS), which combines a digital time domain vision sensor [5] and a novel adaptive digital quantizer. Unlike any other logarithmic sensor reported in the literature, our sensor features a unique digital mode of operation offering a great deal of flexibility and adaptability. Both the logarithmic transfer function and the adaptation feature are obtained by simply tuning the parameters of a digital quantizer. The remainder of this letter is organized as follows: Section II introduces the theory behind the logarithmic response and the adaptation procedure to different intensity levels; Section III reports the validation of the proposed concept through experimental measurements from the prototype chip; Section IV concludes this work.

II. LOGARITHMIC RESPONSE IN A DPS—THEORY

The adaptive logarithmic response is realized by combining a time-domain digital pixel [5] and a novel quantizer, as illustrated in Fig. 1(a). A photodetector denoted as PD is used to convert the input light into a photocurrent I . The photocurrent is then converted to a time domain signal using pulsewidth modulation (PWM). The time domain signal is digitized by the quantizer Q , where the quantization steps are not fixed, but determined iteratively, by the adaptive feedback circuit AF . D_i

corresponds to the digitized photocurrent output for a given iteration i . Based on the current digital code D_i and a primary clock frequency F_{pri} , the AF will set the quantization steps by defining the quantizer's clock frequency F_{var} . The proposed approach is realized using the block diagram shown in Fig. 1(b). A reversed biased photodiode is used to convert the illumination level into a photocurrent I , which discharges the voltage at the sensing node V_n . A comparator (*Comp*) is used to convert the discharging voltage V_n to the corresponding integration time T . When the voltage at V_n reaches V_{ref} , the comparator triggers (*Out*), and an 8-bit digital value produced by the quantizer (an 8-bit counter) is stored in the pixel memory. This is achieved by connecting the output of the comparator (*Out*) to the write signal W of the memory, as illustrated in Fig. 1(b). The AF block is realized through a look-up table and a frequency divider. This generates a variable frequency clock F_{var} , derived by dividing the primary clock, F_{pri} , with an integer value stored in the lookup table, indexed by D_i . These look-up table entries have been calculated so as to produce a logarithmic response in the timing/counting process. While F_{pri} can be considered constant for each exposure, it may be varied between exposures to provide a mean of adapting to different lighting conditions. The integration process is initiated by pulsing the ST_{int} signal high, which will reset the SR latch and switch off transistor Q_1 . When V_n reaches V_{ref} , the comparator triggers and sets the SR latch, which will reset the voltage V_n using the feedback signal (*Rst*) as illustrated in Fig. 1(b). After reset, the voltage at V_n is maintained high until the start of a new integration cycle. The digitized image can then be read out from the pixel array by accessing the pixel level memory.

To derive the timing algorithm required to produce a logarithmic response, the relationship between the photocurrent I and the integration time T is first considered, where

$$T = \frac{(V_c - V_{\text{ref}}) \times C}{I}. \quad (1)$$

C is the photodiode capacitance, while V_c and V_{ref} are the reset and the reference voltages, respectively. The range and the resolution of the conversion are determined by the maximum photocurrent I_{max} (or the minimum integration time T_{min}) and the number of quantization steps available to represent this value q . In the case of the prototype, $q = 255$, as determined by the depth of the in-pixel memory (8 bits). A scaling factor β is also introduced to give further control over the response, such that

$$q = \beta \ln \frac{I_{\text{max}}}{I_{\text{min}}} \quad (2)$$

or

$$I_{\text{max}} = e^{q/\beta} I_{\text{min}}. \quad (3)$$

For the purpose of deriving the timing algorithm, it is assumed that the continuous photocurrent can be represented by an equivalent, discrete approximation $I(D_i)$, where

$$I(D_i) = e^{D_i/\beta} I_{\text{min}} \quad (4)$$

which leads to a discrete approximation of the integration time

$$T(D_i) = \frac{(V_c - V_{\text{ref}}) \times C}{e^{D_i/\beta} I_{\text{min}}}. \quad (5)$$

The conversion time $T_{\text{conv}}(D_i)$ is equal to $T(D_i) - T_{\text{min}}$, as determined by the selection of I_{max} . To find the primary (the highest) frequency required for the conversion, we consider the photocurrent as it changes from I_{max} to $I(q-1)$, then find the difference in integration time between the two values, and consider this to be the period of F_{pri} , which results in

$$F_{\text{pri}} = \frac{1}{T_{\text{min}}(e^{1/\beta} - 1)}. \quad (6)$$

The variable clock F_{var} performs two tasks. First, it compensates for the nonlinear relationship between T and I in (1). Second, it implements the logarithmic function of (4). This is achieved by determining the rate of change of (1) with respect to the photocurrent (dT/dI), where I is set equal to (4). Then, dI is found by taking the derivative of (4) (dI/dD_i) noting that for the discrete approximation, dD_i is always unity. The result is simplified in order to express F_{var} in terms of F_{pri} , which gives

$$F_{\text{var}} = \frac{1}{dT} = F_{\text{pri}} \frac{\beta(e^{1/\beta} - 1)}{e^{(q-D_i)/\beta}}. \quad (7)$$

It can be seen from (7) that F_{var} can be derived from F_{pri} , through division by a constant factor for each value of D_i . In practice, the divisor values are held in a look-up table, and indexed by the counter output D_i , as shown in Fig. 1(b).

III. EXPERIMENTAL SETUP AND RESULTS

In Section II, we have derived the theory behind using an iteratively adaptive quantizer, to realize a logarithmic response DPS. It is very interesting to observe that the requirement of a simultaneous need for high sensitivity and large DR can be met by properly using (6) and (7). Let us assume that we would like to cover a 140-dB DR. Given this DR, it is possible to find the primary clock frequency and the scaling factor β using (6) and (7), respectively. However, using a single log function to cover the whole 140-dB range will result in a very poor resolution, as is the case for a conventional logarithmic pixel. In order to keep the resolution to a reasonable level, we can limit the DR in order to cover a fraction of the 140 dB by the selection of β , and then the logarithmic response can be shifted by the selection of F_{pri} .

To test the operation of the proposed adaptive logarithmic sensor, a prototype sensor array of 64×64 pixels was fabricated using a $0.35\text{-}\mu\text{m}$ CMOS AMIS process. The imager is interfaced to a PC running Linux, which provides a user interface and records the light meter data and test images, as shown in Fig. 2. For the sake of flexibility, the quantizer was implemented off-chip on a microcontroller; however, one should note that implementing the quantizer on-chip together with the image sensor array is very straightforward as it requires only digital circuitry and a look-up table.

In order to evaluate the DR of our sensor, the integration time T was measured for a wide range of illumination set by the light source shown in Fig. 2. Integration times of 1 s to 10^{-5} s were measured for illumination levels varying between 1 to 10^5 lux, which corresponds to 100-dB DR. It should be noted that the 100-dB limitation was set by the optical setup limitation and not by the sensor. Fig. 3 shows the effect that the selection of β has on the logarithmic response, where the slope (and, therefore, the

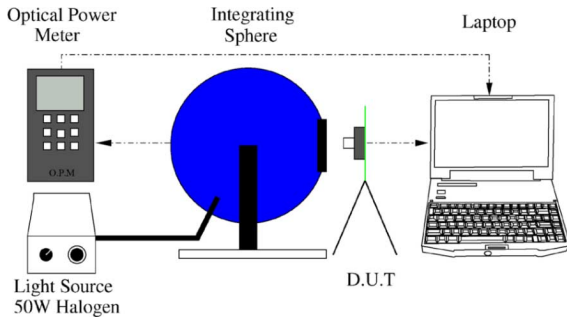


Fig. 2. Diagram of the test setup. The laptop records the digital data from the device under test (DUT), while the light source is varied over its full range and light intensity is measured using the optical power meter (OPM). (Color version available online at <http://ieeexplore.ieee.org>.)

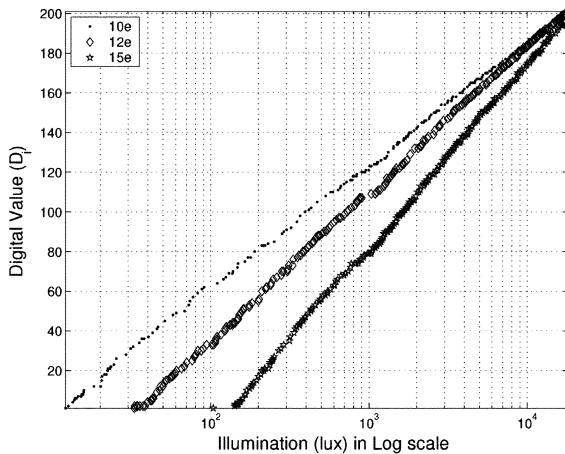


Fig. 3. Experimental measurements of the ADC logarithmic response for $\beta = 10e, 12e,$ and $15e$, with $F_{\text{pri}} = 100$ kHz. Note that the light source in our experimental setup cannot drive the ADC into saturation (maximum $D_i \approx 200$).

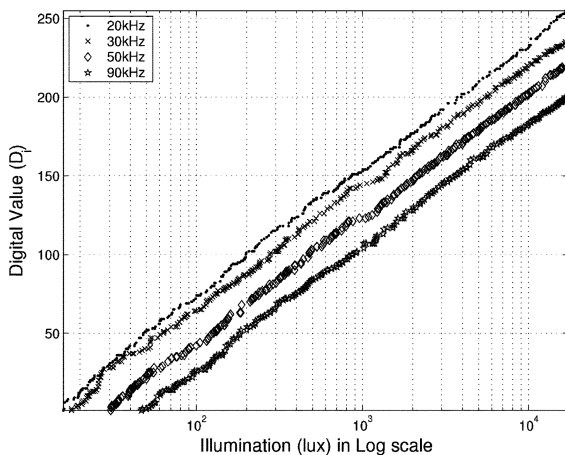


Fig. 4. Experimental measurements of the ADC response, demonstrating the effect of altering F_{pri} for a constant $\beta = 13e$. $F_{\text{pri}} = 20, 30, 50,$ and 90 kHz.

range) of the conversion varies with the choice of β (note that for convenience, β is expressed as a multiple of e).

Fig. 4 demonstrates how the response can be shifted by modulating the clock frequency F_{pri} (in this case $\beta = 13e$). The logarithmic response as well as the DR and pixel's response adaptation process are, therefore, experimentally validated. The

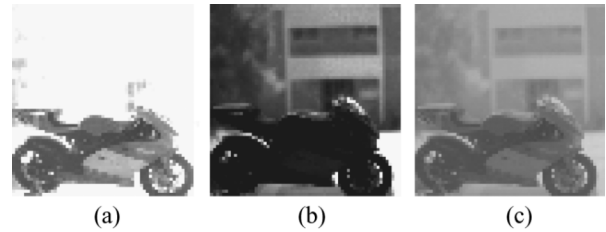


Fig. 5. Experimental sample images acquired from the 64×64 imager contrasting linear and logarithmic responses. (a) Linear exposure set for foreground level ($F_{\text{pri}} = 25$ kHz). (b) Linear exposure set for background level ($F_{\text{pri}} = 150$ kHz). (c) Logarithmic exposure for fixed frequency and scaling factor ($F_{\text{pri}} = 95$ kHz, $\beta = 15e$).

discrete selection of the parameters does result in some discontinuities in the response (as can be seen at 10^3 lux). Further data collection around this point (smaller step size in the illumination) is possible, but here it does highlight the discontinuous nature of the response.

Fig. 5 demonstrates the practical application of the logarithmic response. This figure shows a series of three images (of a $1/17^{\text{th}}$ scale model) framed by a window, where Figs. 5(a) and (b) are captured using a linear response, and Fig. 5(c) is captured using a logarithmic response. It is clear that for a linear response, when the exposure is correct for the foreground, the background is over exposed, and likewise when the background is correctly exposed the foreground is dark. Only the logarithmic response produces adequate detail from both foreground and background.

IV. CONCLUSION

This letter presents a novel system level implementation of an adaptive logarithmic DPS combining a time domain sensing scheme with a novel adaptive digital quantizer. Inspired from the biological photoreceptor's response and in contrast to the conventional logarithmic pixel, the proposed sensor fulfils the challenging requirement of a large DR while maintaining high resolution. Indeed, it was experimentally demonstrated that both the pixel's response and the DR can be adapted using the primary clock frequency of the quantizer as well as discrete binary coefficients stored in the SRAM of the microcontroller. The flexibility and adaptability features of our sensor make it very suitable for a wide range of applications requiring wide DR imaging.

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