Vol. 6(22) Oct. 2016, PP. 3071-3079

Contents list available at IJMEC

International Journal of Mechatronics, Electrical and Computer Technology (IJMEC)

Journal Homepage: www.aeuso.org

PISSN: 2411-6173 - EISSN: 2305-0543

A High Dynamic Range CMOS Image Sensor with a Novel Pixel-Level Logarithmic Counter Memory

Saul D. Freedman and Farid Boussaid

School of Electrical, Electronic and Computer Engineering

The University of Western Australia, Perth, Australia

Phone Number: +61 4 1302 8 959

****Corresponding Author's E-mail:*** 20937392@student.uwa.edu.au

Abstract

In this paper, we propose a CMOS image sensor that exploits multiple capture and spatially varying pixel exposures to achieve a dynamic range of 155 dB, 95 dB higher than a conventional CMOS image sensor. The proposed sensor also utilizes a novel pixel-level counter memory to enhance the sensor's dynamic range and fill factor. Here, the logarithms of counter values used in measurements of incident light intensities are approximated and stored in memory within each pixel. Since these logarithmic values can be represented by a smaller number of bits, each pixel has a smaller area dedicated to memory, allowing a higher fill factor. The proposed CMOS image sensor is well suited to outdoor automotive and mobile robotic applications.

Keywords: *CMOS image sensor, fill factor, high dynamic range, logarithmic approximation, multiple capture, spatially varying pixel exposures.*

I. INTRODUCTION

In recent times, digital imaging systems have increasingly made use of CMOS image sensors, instead of the traditional charged-coupled device (CCD) sensors [1-3]. This is because CMOS image sensors provide higher readout speeds, a lower power consumption and full integration with other circuitry on a single chip [1-3]. Indeed, CMOS image sensors are now widely adopted in consumer electronics such as digital cameras and mobile phones, as well as other areas including medicine and the automotive industry [1, 4, 5]. The unique properties of CMOS image sensors has spurred the development of a new generation of low-power mobile imaging systems capable of performing real-time processing, for applications such as automotive traffic detection systems, robotic navigation systems or electronic low vision aids [6-8]. However, most of these systems need to operate in environments where the dynamic range (DR), i.e. the range of light intensities, is often prohibitively high for scenes to be successfully imaged by conventional CMOS image sensors [1, 4, 7]. The high end DR of a conventional CMOS image sensor is limited by the highest photocurrent i_{ph} that it can measure for a given image capture period, or equivalently, by the saturation limit $V_{\max}$ of the nondecreasing voltage signal generated by integrating the photocurrent over this period [1, 4]. As such, several techniques have been proposed to extend the sensor's DR by effectively bypassing this saturation limit, both at the pixel level [1, 4, 9-13] and the image sensor level [14-16]. Multiple capture is such a technique, in which the effective integration time of each pixel will depend on the time it takes to saturate [4]. This enables a high DR and a high signal-to- noise ratio (SNR) to be achieved [4, 17]. Additionally, the low-complexity circuitry used to implement this technique [4, 17] provides the sensor with a higher fill factor (i.e.

Article History:
IJMEC DOI: 649123/10222
Received Date: Dec. 03, 2015
Accepted Date: Sep. 08, 2016
Available Online: Oct. 01, 2016

ratio between the area of the pixel's photodiode and the pixel's total area [1]). However, the DR extension achieved by multiple capture is significantly lower than that achieved by several other pixel-level DR extension techniques [4, 17]. In order to address this issue while taking advantage of the benefits of multiple capture, we propose a CMOS image sensor that combines multiple capture with sensor-level DR extension via spatially varying pixel exposures, thereby allowing different pixels of the sensor array to measure different regions of a scene's light intensity range [14-16].

Our sensor also incorporates a novel p i x e l -level logarithmic counter memory, where logarithmic approximations of counter values used to estimate photocurrents are calculated and stored in memory within each pixel. Storing such a logarithmic approximation requires a smaller memory area than storing the original counter value, and so each pixel's photodiode can occupy a larger area than in an equivalent sensor using a linear counter memory. The proposed sensor therefore achieves a higher fill factor than this equivalent sensor, and hence an improved performance in the presence of noise [18].

The rest of the paper is structured as follows. Section II reviews previously reported DR extension techniques, including multiple capture and spatially varying pixel exposures. In Section III, we describe the operation and architecture of our proposed high DR CMOS image sensor, including its novel pixel-level logarithmic counter memory. Section IV reports the performance of our proposed sensor. Finally, Section V concludes this paper and provides suggestions for future work.

II. REVIEW OF DYNAMIC RANGE EXTENSION TECHNIQUES

A. Time-to-saturation

One pixel-level technique that extends the DR of a CMOS image sensor by bypassing its saturation limit is the time-to- saturation technique, where the time it takes for pixels to saturate is measured, when such saturation occurs [4, 10-12]. Since a pixel's time-to-saturation is inversely proportional to its photocurrent, this technique allows the estimation of saturating photocurrents [4, 10-12]. As a result, the sensor's high end DR is extended [4, 10-12]. The sensor's low end DR can be maintained by estimating nonsaturating photocurrents using their final integrated voltage signal values, as in a conventional sensor [4, 11, 12].

Although the time-to-saturation technique is conceptually simple, the circuitry required is relatively complex, occupying a non-negligible pixel area [4, 17]. This has the effect of either decreasing the pixel's fill factor or increasing the size of each pixel, thereby limiting the image sensor's resolution [1, 4, 18, 19]. Additionally, the noise associated with time-to-saturation measurements results in the sensor's SNR decreasing quadratically with i_{ph} in the extended DR region [4, 17].

B. Synchronous Self-reset

The synchronous self-reset technique extends the high end DR of a conventional CMOS image sensor by increasing its effective well capacity, i.e. the maximum charge that can be stored in the capacitance used to integrate i_{ph} [4, 9]. Here, each pixel's integrated signal is periodically monitored to determine whether it has saturated [4, 9]. When this occurs, it is reset and a counter is incremented [4, 9]. At the end of the integration period, the pixel's photocurrent is estimated from the number of resets stored in the counter and the integrated signal's final value [4, 9].

Incorporating this final value in the photocurrent estimate accounts for the fact that the integrated signal will not, in general, reset at or just before the end of the integration period. However, this technique does not account for the amount of time during which the integrated signal may be temporarily saturated between each pair of consecutive sample times. This means that errors can become significant for high photocurrents. Since each pixel operates independently, each pixel requires its own internal counter [4, 9], which significantly increases the pixel area. Additionally, due to the offset variation introduced by each reset of the integrated signal, the sensor's SNR again decreases quadratically with i_{ph} in the upper end of the extended DR region [4, 17].

C. Multiple Capture

In a CMOS image sensor using the multiple capture DR extension technique, each pixel's photocurrent is estimated via nondestructive multiple sampling of its integrated signal and via the last sample before saturation algorithm [1, 4, 13]. Here, the effective integration time of each pixel is determined by its time-to-saturation. As a result, the sensor's high end DR is increased [1, 4, 13]. There are various ways of implementing this technique, such as using exponentially increasing sample times [13]. However, in this paper we propose a simple implementation similar to the implementation, in which a column-level counter increments periodically during the integration period. Each time the counter increments, the pixel's integrated signal is evaluated. If this signal has not saturated, then its value and the counter value are written into the pixel-level memory overwriting any previously stored values. At the end of the integration period, each pixel's last sample before saturation (consisting of an integrated signal value and a counter value) is read out and used to estimate its photocurrent using [4]:

$$i_{ph} = \frac{C_D v(jt_{capt})}{jt_{capt}} \tag{1}$$

Where *CD* is the capacitance of the pixel's photodiode, t_{capt} is the sampling period and *j* and $v(jt_{capt})$ are the final counter value and final integrated signal value before saturation, respectively. At the start of the next integration period, the memory in each pixel, and the value on each counter, is reset to 0. If the integrated signal value and the counter value stored in the pixel's memory are still both 0 at the end of an integration period, then the signal has saturated before the first sample time. In this case, the photocurrent is estimated as if saturation occurred at this sample time.

In the multiple capture implementation in [4], all of the pixel's samples are read out. Weighted averaging of these samples is then carried out to reduce the sensor's effective readout noise [4]. This allows an extension of the sensor's low end DR [4]. Since only one sample is read out from each pixel in the proposed implementation, such weighted averaging is not performed. This greatly relaxes the sensor's on-chip memory and digital signal processing (DSP) requirements [4]. Additionally, since DSP and pixel readout are the dominant sources of power consumption [4], the proposed implementation consumes significantly less power, and is therefore more suitable for use in mobile imaging systems [7].

The SNR of an image sensor using multiple capture remains relatively constant throughout the extended DR, as a result of each pixel's integration time being matched to its time-to-saturation [4, 17]. A high SNR is thus achieved even for high photocurrents. Additionally, because the circuitry required for this technique is simpler than for time-to-saturation and synchronous self-reset, it can occupy a smaller area [4, 17]. Therefore, for a given pixel size, multiple capture provides a higher fill factor than the other two techniques.

D. Spatially Varying Pixel Exposures

In addition to pixel-level DR extension techniques, a conventional CMOS image sensor's DR can be extended using spatially varying pixel exposures [14-16]. Here, a filter array is placed over the sensor's main pixel array so that different pixels can detect different levels of the incident light intensity [14-16]. The estimate of a pixel's detected intensity and its known exposure value are used to estimate the incident intensity [14-16]. Therefore, although the pixel's minimum and maximum detectable photocurrent values, i_{min} and i_{max}, remain unchanged, its effective i_{min} and i_{max} values both increase by a factor inversely proportional to its exposure value. It follows that a high DR can be achieved by alternating between low and high exposure values throughout the array, thereby allowing a large light intensity range to be measured over different pixels [14-16]. Here, the sensor's DR is the ratio between the effective i_{max} value of a pixel with the lowest exposure in the array and the effective i_{min} value of a pixel with the highest exposure [14]. It is important to note that this DR extension comes at the cost of a slightly reduced spatial resolution, since the sensor's output images are generated by interpolating the incident light intensity estimates of each group of neighbouring pixels [14- 16]. Additionally, since the fabrication process of filter arrays is imperfect, with variations introduced between ideally identical filters [20], the filter array introduces additional fixed pattern noise (FPN) to the sensor, thereby reducing its SNR.

III. THE PROPOSED HIGH DYNAMIC RANGE CMOS IMAGE SENSOR

A. Dynamic Range Extension

In order to achieve a high fill factor, a high SNR and a relatively large high end DR extension, our proposed sensor uses multiple capture as its pixel-level DR extension technique. In order to calculate the internal DR achieved by our sensor, we assume that, as in [4], t_{capt} = 150µs, the sensor has a well capacity of Q_{max} = 125,000 (in units of electrons), and the only noise limiting i_{min} is readout noise, with zero mean and average power $\sigma^2_{readout} = (35e^-)^2$. Note that this last assumption requires that the sensor performs correlated double sampling (CDS) in order to eliminate offset FPN and reset noise [1, 4]. Also note that this value of σ2readout incorporates the sensor's nonnegligible quantization noise [4]. Finally, our sensor uses an 8-bit counter, so the total integration time of each image capture frame is given by

$$t_{int} = (2^8 - 1)t_{capt,} \tag{2}$$

with *t*int = 38.25 ms. With the above assumptions, the sensor's internal values of *i*min, *i*max and DR are given by

$$i_{min} = \frac{q\sigma_{readout}}{t_{int}} \tag{3}$$

$$i_{max} = \frac{qQ_{max}}{t_{capt}} \tag{4}$$

And

$$DR = \frac{i_{max}}{i_{min}} = \frac{Q_{max}t_{int}}{\sigma_{readout}t_{capt}} \tag{5}$$

where q is the elementary charge. We have thus i_{min} = 0.147 pA, i_{max} = 0.134 nA and DR = 119 dB. Note that this is much higher than the 40–60 dB DR of a conventional CMOS image sensor [1], but significantly lower than the 136–156 dB DR and 161 dB DR achieved in [4] with the time-to-saturation and synchronous self-reset techniques respectively.

In order to achieve a DR comparable to these higher values, our proposed sensor combines multiple capture with spatially varying pixel exposures. We use four exposure values in our filter array, in a configuration [14] that has shown to be effective. Specifically, we used the exposure pattern shown in Fig. 1, with successive exposure values increasing by a factor of 4. The ratio between our maximum and minimum exposure values, e_{max} and e_{min}, is therefore 43 = 64. The total DR of our sensor is given by [14]:

International Journal of Mechatronics, Electrical and Computer Technology (IJMEC)
Universal Scientific Organization, www.aeuso.org
PISSN: 2411-6173, EISSN: 2305-0543

$$DR = \frac{i_{max}}{i_{min}} \frac{e_{max}}{e_{min}} \tag{6}$$

e_4	e_1	e_4	e_1	e_4	e_1	e_4	e_1
e_3	e_2	e_3	e_2	e_3	e_2	e_3	e_2
e_4	e_1	e_4	e_1	e_4	e_1	e_4	e_1
e_3	e_2	e_3	e_2	e_3	e_2	e_3	e_2
e_4	e_1	e_4	e_1	e_4	e_1	e_4	e_1
e_3	e_2	e_3	e_2	e_3	e_2	e_3	e_2
e_4	e_1	e_4	e_1	e_4	e_1	e_4	e_1
e_3	e_2	e_3	e_2	e_3	e_2	e_3	e_2

Fig. 1. The exposure pattern of the filter array used in the proposed sensor, with $e4 = 4e3 = 16e2 = 64e1$.

where i_{max} and i_{min} are the sensor's maximum and minimum detectable photocurrents without the filter array. The filter array therefore increases the sensor's total DR by a factor of 64, or equivalently, by 36 dB. As such, we achieve a total DR of 155 dB, which is 95 dB higher than that of a conventional CMOS image sensor [1]. Also note that the proposed sensor achieves a frame rate of $1/t_{int} \approx 26$ frames per second, and hence the sensor is capable of real-time imaging [21].

B. Pixel-level Logarithmic Counter Memory

Our proposed sensor performs multiple capture using the method described in Section II.C, but with a novel pixel-level logarithmic counter memory. Fig. 2 gives a block diagram of the sensor's counter–memory architecture. Here, before being written to pixel memory, each counter output is converted to a base 2 logarithmic approximation. Our sensor uses 8-bit counters, and hence each counter output k can be represented in binary as

$$k_{binary} = \text{b7b6...b2b1b0}. \tag{7}$$

If the leading nonzero bit of the counter output is b_a, then its logarithmic approximation has a decimal value of

$$k_{log} = \begin{cases} 0, & a = 0 \\ a + b_{a-1} & a > 0 \end{cases} \tag{8}$$

This log approximation can be calculated from the exact counter output k using circuitry as simple as standard logic gates. Additionally, k_{log} is a very good approximation of the rounded value of $\log_2(k)$, with errors introduced for only 18 of the 255 possible nonzero counter outputs. In these cases,

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PISSN: 2411-6173, EISSN: 2305-0543

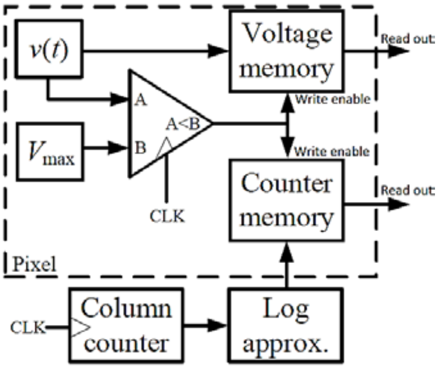

Fig. 2. A block diagram of the proposed sensor's counter–memory architecture.

$\log_2(k)$ has a value slightly above $n + ½$, where n is an integer, but k_{log} is rounded down instead of up. Note that the counter value is never 0 when it is to be written to pixel memory. As a result, we do not need to define a log approximation of 0. Now, at the end of each integration period, the final counter log approximation before saturation, j_{log}, is read out from each pixel. The pixel's photocurrent is estimated as in (1), but with the exact value of the final counter output before saturation replaced with the approximation given by

$$j_{approx} = 2^{j_{log}} \tag{9}$$

Here, the pixel's photocurrent is still estimated as having caused saturation at the first sample time if the values stored in the pixel's memory are both 0 at the end of the integration period. From (7) and (8), we see that the maximum value of k_{log} is 8, and so only 4 memory bits are required to store this value, as opposed to the 8 memory bits required to store the exact counter value. Therefore, compared to a standard linear counter memory, each pixel requires half the memory to store a representation of the counter output. It follows that each pixel's photodiode can occupy a larger area, thereby allowing a greater fill factor. This means that the sensor has a greater SNR, as well as an enhanced sensitivity to incident light [18]. Note that since the circuitry used to calculate the counter's log approximation is located outside of the sensor's pixels, as shown in Fig. 2, this circuitry does not degrade the sensor's fill factor.

IV. PERFORMANCE EVALUATION

In order to test the performance of our proposed sensor and its pixel-level logarithmic counter memory, we have compared its output image quality with that of a high DR sensor using DR extension methods that use a conventional linear counter memory. Note that the sensors do not include color filter arrays, and so they produce grayscale images. Additionally, apart from the interpolation required due to the spatially varying pixel exposures, the outputted images have not been post-processed in any way.

Fig. 3 shows the outputs of the two sensors when imaging the panoramic high DR scene from [22]1, which is representative of many of the scenes that a sensor could image. By comparing Fig. 3 (a), the image outputted by the sensor with the linear counter memory, with Fig. 3 (b), the image outputted by the proposed sensor, we see that the latter image contains significant errors. Namely, many of the gradual gray level gradients in Fig. 3 (a) are replaced with well-defined patches of brighter and darker grays, and this results in the loss of some details (e.g. imaged clouds). This is because each k_{log} value used in the proposed sensor approximates a range of counter outputs k. Our proposed sensor would therefore not be suitable for use in digital imaging systems where the output images must be aesthetically pleasing, such as consumer digital cameras. It is also important to note that due to the multiple sampling used in multiple capture, the sensor could not be used in a system requiring a very high frame rate and a high DR, such as a high-speed camera, even with a reduced *t*int value [4]. However, all of the objects in Fig. 3 (b), including the vehicles, the buildings, the chandelier and even the piece of paper near the center of the photo, are very well defined. The proposed sensor is therefore highly suited to being used in mobile object detection systems operating in high dynamic range environments, including automotive traffic detection systems, outdoor robotic navigation systems and electronic low vision aids. Specifically, our sensor would provide such a system with its high DR, real-time imaging requirements, and high fill factor.

(a)

(b)

Fig. 3. The outputs of the evaluated sensors when imaging the panoramic high DR scene from [22]. (a) The output of the sensor with the linear counter memory. (b) The output of the proposed sensor.

CONCLUSION

In this paper, we have proposed a CMOS image sensor that combines multiple capture, spatially varying pixel exposures and a novel pixel-level logarithmic counter memory in order to achieve a DR of 155 dB, 95 higher than that of a conventional CMOS image sensor. In our sensor, logarithmic approximations of the counter outputs used in the multiple capture technique are stored in the pixel-level memory. This provides the sensor with a higher fill factor than an equivalent sensor with a linear counter memory. With real-time imaging capability, the proposed sensor is well suited to automotive and outdoor mobile robotic applications. Indeed, our sensor achieves a frame rate of about 26 frames per second, and therefore meets the real-time imaging requirements of these systems. Additionally, the multiple capture implementation used in our sensor achieves a lower power consumption than the implementation used in [4], and hence the technique we use is more appropriate for these mobile systems. Future work will involve optimizing the configuration of exposure values in the sensor's filter array, in terms of its output image quality. For example, the sensor's image quality may improve if more than four exposure values are used in the array, or if they are arranged in a random configuration rather than a repeating pattern [14]. Additionally, the sensor's performance will be evaluated using enhanced models that incorporate the additional FPN introduced by the filter array, as well as the additional fill factor provided by the logarithmic counter memory. This will allow us to quantitatively measure the effects of these parameters on the sensor's performance, for example in terms of SNR. The sensor's exposure filter array will also be combined with a color filter array, as in [15], in order to test its performance in object detection systems that require color imaging.

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