Segmented-base CMOS Image Sensor for Machine Vision Application

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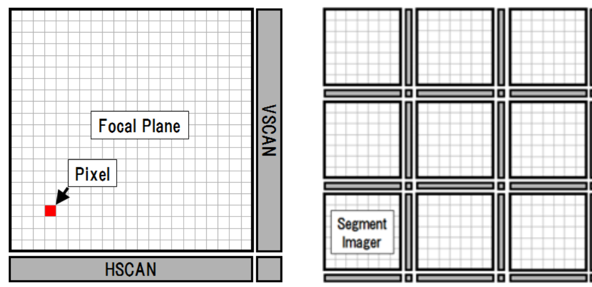
ABSTRACT

In this paper, a CMOS image sensor whose focal plane is divided into several segments for machine vision application and an effective imaging method using segmented-base CMOS image sensor are presented. The proposed architecture of the image sensor adjusts imaging parameters on a segmented base. A segment is coupled to an external processing engine, which enables faster readout and real-time processing as well as co-operation among the segments. 1st prototype chip was proposed and introduced in [1]. We describe an improved sensor performance of the newly designed 2nd prototype chip, in which 128 × 128 × 12 segments, extended dynamic range pixel and a 10-bit, 2.5M-sample-per-second pipelined analog-to-digital converter are integrated [2]. Simulation results indicate that this chip achieves 152 fps per segment and the ADC dissipates less than 6.5mW. In addition, we describe the imaging method using 1st prototype chip which adapts exposure time and frame rate to objects segment by segment based on their brightness and motion. Experimental results of FPGA implementation show the effectiveness of the adaptive imaging.

Keywords: Segmented-base CMOS image sensor, Extended dynamic range, Pixel-level reset, Pixel Sequential readout, Pipelined ADC, Segmented-base imaging, FPGA implementation.

1. INTRODUCTION

Machine vision is used for automatic and intelligent systems such as advance car safety and surveillance systems. In machine vision system, wide dynamic range and high frame rate are important performances of image sensor for recognition processing. With wide dynamic range, both overexposure and underexposure within an intrascene frame can be suppressed and then the detail contrast of the target objects can be identified for recognition processing. Also with high frame rate, a pixel displacement of adjacent frames becomes minimal in certain optical setting. Having small displacement improves machine vision functionalities such as target object tracking and recognition. Utilizing a conventional single-imaging-parameter-based CMOS image sensor for these applications raises issues because (1) a trade-off between the pixel resolution and frame rate cannot be avoided, and (2) the dynamic range cannot be sufficiently extended without a large amount of latency due to multiple frame capture with different exposure times and reconstruction [3]. In order to resolve these issues without affecting the image capturing capability for machine vision, we have proposed segmented-base readout on the focal plane of image sensor [1, 2]. We have been investigating the CMOS image sensor whose focal plane is divided into several segments for machine vision application. The segmented-base image sensor can achieve wide dynamic range and high frame rate by controlling temporal resolution individually at any segment on the focal plane without the aforementioned issues. Also, machine vision requires high computation to conduct special functionalities such as feature extraction and physical parameter estimation for recognition. The segmented-base image sensor has suitable structure for highly parallel processing by coupling one segment with one processor. In addition, in order to confirm the effectiveness of segmented-base structure, we propose a brightness-and-motion adaptive imaging method using the 1st prototype segmented-base image sensor.



(a) Conventional (b) Segmented- base

Fig.1 The conceptual diagram of image sensor structure

2. SEGMENTED-BASE IMAGE SENSOR CONCEPTS

The conceptual diagram of structure for both the conventional and segmented-base image sensors is depicted in Fig. 1. The conventional structure has one focal plane. It can control imaging parameters such as exposure time and frame rate not locally but globally on the focal plane.

On the other hand, the segmented-base structure consists of several segments on the focal plane. There are two benefits. Each segment has a readout circuit to control imaging parameters independently at any segment on the focal plane. This feature enables exposure time and frame rate to be optimized segment by segment to accommodate on high/low bright regions or regions with moving objects. For high/low bright regions, the image sensor can obtain intrascene wide-dynamic-range images by adjusting exposure time. For regions with moving objects, the image sensor can increase temporal resolution by adjusting frame rate. Another benefit is that the segmented-base structure is suitable for highly parallel processing. A segment can be coupled to an external processor engine which realizes tight feedback paths from the processor engine to the pixel array to enable dynamically to change exposure time and frame rate and to realize faster readout and highly parallel processing in real-time.

3. TEST CHIP SPECIFICATION

We have developed two prototype chips in using a 0.18-um standard CMOS process. 1st prototype chip is introduced in [1]. 1st prototype chip is 44fps, 256×512 segmented-base CMOS image sensor which consists of 8 segments. 2nd prototype chip is an 84-dB extended dynamic range, 152-fps, 512×384 segmented-base CMOS image sensor which consists of 12 segments and the same number of pipeline ADC as shown in Fig. 2 [2]. Table 1 shows the chip specifications. Each segment has 128×128 pixels. The pipeline ADC has 10-bit, 2.5-MS/s.

Image discontinuity exists in the case of the segmented-base image sensor. It is because readout circuits which become insensitive area reside on the boundaries of the segments. This is one of the drawbacks of this sensor and must be minimized. Each segment consists of the readout circuits necessary to enable rolling shutter operation. Namely, they are horizontal/vertical scanners, high voltage row drivers for soft reset operation, column sampling circuits and level shifters. Among them, the column sampling circuits tend to be the tallest. Thus, in order to completely eliminate the column sampling circuits, we implemented pixel sequential readout scheme which is depicted in Fig. 3. The photo- and pixel reset signals are directly transferred from the pixel to the sampling circuits at the chip peripherals without a column-level sampling operation. The settling time of a pixel SF to the dual voltage follower was designed to be <200 ns, estimating that the parasitic capacitances of the pixel SF and the segment output SF were 1.5 pF and 3 pF, respectively. The settling performance of the dual voltage follower was also designed to be <0.1% in 200 ns with a 400 fF sampling load. To make use of the ADC at full speed, two dual

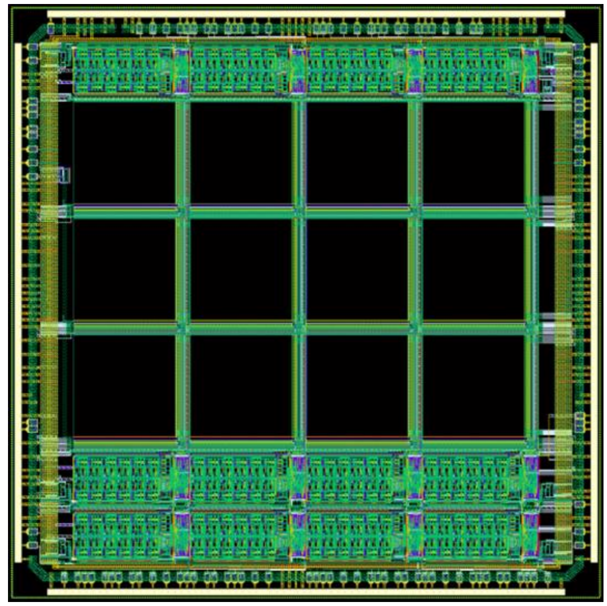


Fig.2 Chip layout pattern

Table 1 Chip specifications

Technology	ROHM 0.18-µm 1P5M CMOS
Die size	5,180 µm (H) × 5,180 µm (V)
Net pixel count	0.2 M pixels
Pixel array	128 (H) × 128 (V), 12 segments
Pixel size	7 µm × 7 µm
Aperture ratio	17%
Maximum frame rate	152 fps
Power supply voltage	3.3 V
Power consumption	209.9 mW (Analog)

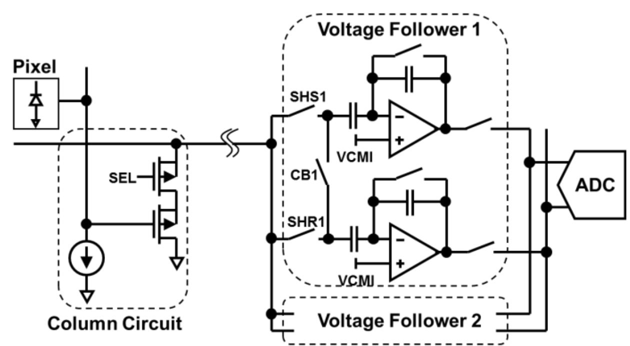


Fig.3 Pixel sequential readout chain

voltage followers were used. The total pixel readout period is 400 ns (200 ns each for the photo-signal and pixel reset voltage sampling operations). This corresponds to 152 fps for all pixels. Each segment integrates its own ADC and chip output channel; thus, as a whole, the image sensor can operate at frame rates up to 152 fps.

The 84-dB extended dynamic range is realized by a pixel-level reset control supported by the pixel sequential readout scheme. The shutter operation for each pixel can be controlled externally. In conjunction with the pixel sequential readout scheme, the exposure time can be set to 1/16384th of the frame readout time because the shortest integration time is a one pixel readout period. The ratio of the maximum and minimum exposure times corresponds to 84dB and the dynamic range is extended by the same amount. Therefore, we realize 144dB (60dB+84dB) as total dynamic range. We also compensate the pixel FPN which is caused at pixel-level reset control using the conventional individual reset pixel [4]. The pixel has an X-Y addressing circuit to independently reset the pixels. We achieve the compensation of the pixel FPN by adding minuscule constant current sources to the conventional pixel as shown in Fig. 4. Transistors M5 and M6 are added from [4]. By adding M5 as a very small constant current source, node Vx is pinned and returns to the virtual ground by feeding back the current from the ground. When the virtual ground is disturbed by the clock feedthrough, the same amount of change with the opposite polarity is injected back into the photodiode because Vx becomes slightly below from the virtual ground which creates the drain-to-source voltage of M5. Transistor M6 is also added to suppress the drooping.

A pipelined ADC is integrated for each segment. Thus, there are a total of 12 ADCs on a chip. A pipelined ADC is suitable for a segmented-base CMOS image sensor because (1) it resides on the chip peripheral, and not on the column, and (2) it generates the ADC codes on each cycle that matches the pixel sequential readout timing. A segmented-base CMOS image sensor requires a short column height to minimize image discontinuity.

4. ADAPTIVE IMAGING

We propose a segmented-base adaptive imaging method using 1st prototype chip to get wide dynamic range and high temporal resolution images. The adaptive imaging method consists of two functions. First is adaptive for brightness to widen dynamic range. Second is adaptive for motion to increase high temporal resolution.

Brightness adaptive imaging is to control exposure time based on object brightness segment by segment. It is suitable to widen dynamic range. It improves accuracy of recognition. In order to suppress underexposure and overexposure and keep a brightness average value close to the median, this function detects underexposure and overexposure by comparing numbers of low bright pixels and high bright pixels to thresholds Th_B, Th_W respectively and calculates the brightness average value segment by segment. In the case when the number of low bright pixels is more than Th_B, this function detects underexposure and increases the exposure time two times. In the case when the number of high bright pixels is more than Th_W, this function detects overexposure and decreases the exposure time by half. Also in the case when underexposure and overexposure are not detected, this function

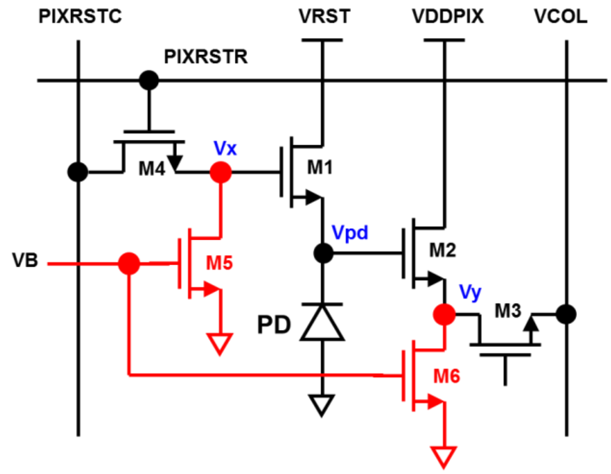


Fig.4 Modified individual reset pixel

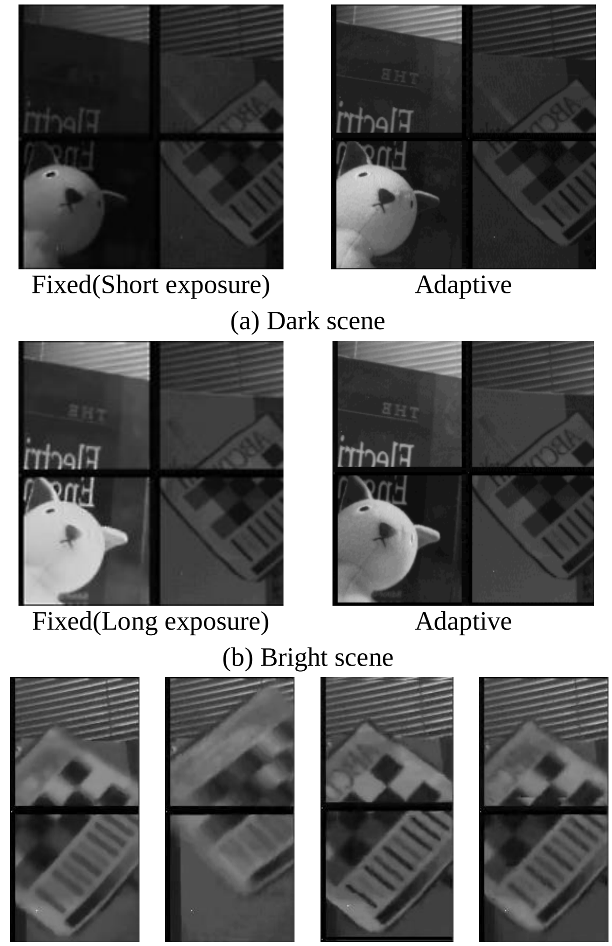
increases/decreases the exposure time to make the brightness average value between thresholds Th_L and Th_H. The brightness adaptive imaging is done by repeating this procedure. An advantage of the brightness adaptive imaging comparing other wide dynamic range imaging methods are (1) it can achieve to extend dynamic range without a large amount of latency due to multiple-frame capture, and (2) a contrast is not compressed.

Motion adaptive imaging is to adjust frame rate based on moving object detection segment by segment. It is suitable to suppress motion blur and increase correlation of continuous frame for moving objects by increasing the frame rate. It improves accuracy of object tracking. In order to increase the frame rate for segments with moving objects, it detects moving object by background differential technique for each segment. Moving object is detected by difference between background and referential images. If the number of high value pixels in the differential image is more than a threshold Th_{OD}, it detects a moving object. After detecting the moving object, it changes the frame rate of object-detected segment to a high frame rate. Additionally, it decreases the threshold Th_{OD} of 8-neighbor segments to a smaller threshold Th'_{OD} in advance. It enables the detection of 8-neighbor segments to be more sensitive for moving object for next frame. The motion adaptive imaging is done by repeating this procedure. An advantage of motion adaptive imaging are (1) it can achieve to increase the temporal resolution in regions with moving object, (2) it keeps high sensitivity in regions without moving objects, and (3) it reduces the redundancy of transmission data by capturing a background with a low frame rate.

Based on the above, the adaptive imaging method is operated by switching between the brightness adaptive imaging and the motion adaptive imaging segment by segment. Each segment operates the moving object detection. The result of moving object detection decides which adaptive imaging segment operates. For segments with moving objects, the motion adaptive imaging is operated. For other segments, the brightness adaptive imaging is operated.

5. EXPERIMENTAL RESULTS

To verify the proposed adaptive imaging method, we have implemented this algorithm in an FPGA using 1st chip. Moving object with a brightness change was captured by 4 segments. We set threshold values (Th_B, Th_W, Th_L, Th_H, Th_{OD}, Th'_{OD}) = (3000, 3000, 58, 188, 128×128, 128×128/2). Fig. 5 shows results for the fixed imaging and the adaptive imaging. Fig.5 (a), (b) show comparison of fixed exposure with adaptive exposure for dark and bright scene. In the case of dark scene, although fixed short exposure causes underexposure on top left, adaptive exposure suppresses the underexposure. In the case of bright scene, although fixed long exposure causes overexposure on bottom left, adaptive exposure suppresses the overexposure. Fig.5 (c) shows comparison of fixed normal frame rate with adaptive frame rate for moving object. In the case of fixed normal frame rate, object movement between frames is large. On the other hand, adaptive frame rate increase the correlation between frames. By the adaptive imaging, suppression of underexposure and overexposure and the increasement of the correlation of continuous frames in the segments with moving object can be confirmed.



t frame *t*+1 frame *t* frame *t*+1 frame
Fixed(Normal frame rate) Adaptive
(c) Moving object

Fig.5 Results for the adaptive imaging

6. SUMMARY

An 84-dB extended dynamic range, 152-fps, 512 × 384 2nd prototype segmented-base CMOS image sensor and adaptive imaging method using 1st prototype segmented-base CMOS image sensor have been presented. As for 2nd prototype segmented-base CMOS image sensor, image discontinuity is reduced by implementing pixel sequential readout scheme. 84-dB extend dynamic range is realized by a pixel-level reset control. The 10-bit, 2.5-MS/s pipeline ADC is integrated. As for the adaptive imaging method, it realizes to get wide dynamic range and high temporal resolution images by controlling exposure time and frame rate segment by segment.

Future work includes realizing higher frame rate, ensuring more flexibility on the pixel-level wide dynamic range functionality, and improving accuracy of adaptive imaging algorithm by introducing object tracking processing and using luminance histogram.

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REFERENCES

[1] T. Otaka, T. Yamasaki, and T. Hamamoto: "An 8-segmented 256x512 CMOS Image Sensor for Processing Element-Coupled Unified System in Machine Vision Application," Proc. of IEEE International NEWCAS Conference, pp. 329-332, 2012.
[2] T. Otaka, T. Yamazaki, and T. Hamamoto: "An 84-dB Extended Dynamic Range, 152fps, 512x384 Segmented-base CMOS Image Sensor with a 10-bit, 2.5-MS/s, 6.5-mW Pipelined ADC," Proc. of IEEE ISPACS Symposium, pp. 630-635, 2012.
[3] M. Mase, S. Kawahito, M. Sasaki, Y. Wakamori and M. Furuta: "A Wide Dynamic Range CMOS Image Sensor with Multiple Exposure-Time Signal Outputs and 12-bit Column-Parallel Cyclic A/D Converters," IEEE J. Solid-State Circuits, vol. 40, no. 12, pp. 2787-2795, 2005.
[4] O. Yadid-Pecht, B. Pain, C. Staller, C. Clark, and E.R. Fossum: "CMOS Active Pixel Sensor Star Tracker with Regional Electronic Shutter," IEEE J. Solid-State Circuits, vol. 32, no. 32, pp. 285-288, 1997.