Micro-Digital Sun Sensor: an Imaging Sensor for Space Applications

Ning Xie[1], Albert J.P. Theuwissen[1,2], Bernard Büttgen[1],
[1]Delft University of Technology, Delft, The Netherlands
[2]Harvest Imaging, Bree, Belgium

Henk Hakkesteegt[3], Henk Jasen[3], Johan Leijtens[3]
[3]TNO, Delft, The Netherlands
E-mail: n.xie@tudelft.nl

Abstract- **Micro-Digital Sun Sensor is an attitude sensor which senses relative position of micro-satellites to the sun in space. It is composed of a solar cell power supply, a RF communication block and an imaging chip which is called APS+. The APS+ integrates a CMOS Active Pixel Sensor (APS) of 512×512 pixels, a 12 bit Analogue to Digital Converter (ADC), digital Input and Output (I/O) circuits, timing signal generators and drivers, and digital signal processing circuits for centroid calculation. The paper describes the implementation of a prototype of the μDSS APS+ using a standard 0.18μm CMOS process. As a space application, it is particularly characterized by its low power consumption. The reduction of power consumption is mainly achieved by windowing, which is enabled by a specific active-pixel design in APS. The functions of the blocks in APS+ are tested. The test results of a test chip which contains 368×368 pixel array will be discussed following in the paper.**

I. INTRODUCTION

The μDSS system is employed on micro-satellite in order to detect the satellite's attitude angle with respect to the sun. The basic working principle is illustrated in Fig. 1. The sun is considered as a point light source in this application. The sun sensor, which is placed on the satellite, has a thin membrane above the chip surface. The membrane blocks the sunlight, with exception of a small pinhole. In this way, the sunlight goes through this pinhole leaving a sun spot on the image sensor array. The size of the pinhole is approximately 50 micron meter. The APS reads out this sun spot's location on the focal plane. Based on this information, the digital processing circuit will calculate the sun spot's center location, and furthermore attitude angle of the satellite with respect to the sun. The attitude angle is fully determined by angel α and θ in Fig. 1. The specification is to detect values for θ within ±64°. In order to fully cover 360° range, three uDSS are required for one satellite. For this application, the size of the image sensor array is 512×512. The pixel pitch is 6.5μm. The size of the sun spot on the image sensor array is about 10 ×10 pixels.

Fig. 2 is the diagram of the μDSS. The solar cell supplies power to the whole system; RF block is for communication purpose; the APS+ is the core of the whole chip. APS+ is built up with the following main blocks:

1. Digital I/O circuits, includes input and output ports to communicate with RF block.
2. Timing signal generator and drivers. In order to achieve low power consumption and high speed, the APS will be operated in different modes. This block will generate timing signals under different working modes.
3. APS. The image sensor is composed of a 512×512 pixel array and read out circuit.
4. A 12-bit pipeline ADC.
5. Digital signal processing circuit, which will do centroid calculation according to specific algorithm.

These blocks will be discussed in detail in the following sections.

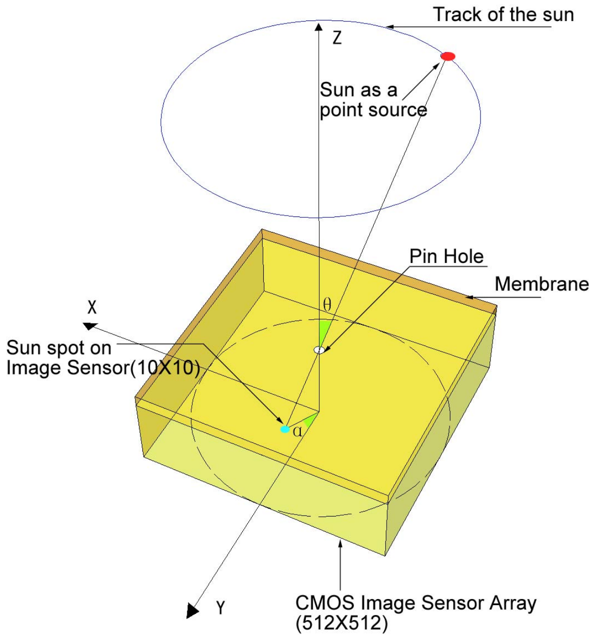

Fig. 1. Working principle of the μDSS

II. APS IMAGE SENSOR

For space application, CMOS-based sensor set-up has a number of advantages over CCD-based image sensor. CMOS enables windowing due to the active pixel concept, and it allows for integrating signal processing circuit on-chip. By means of windowing, only the portion of the pixel array, which is relevant for the post-processing, is scanned in order to reduce the readout cycle. Thus, higher speed and lower power consumption are achieved. The integration of on-chip signal processing capability leads to more compact system-on-chip (SOC) and also optimized power efficiency. Furthermore, a CMOS image sensor is more tolerant to

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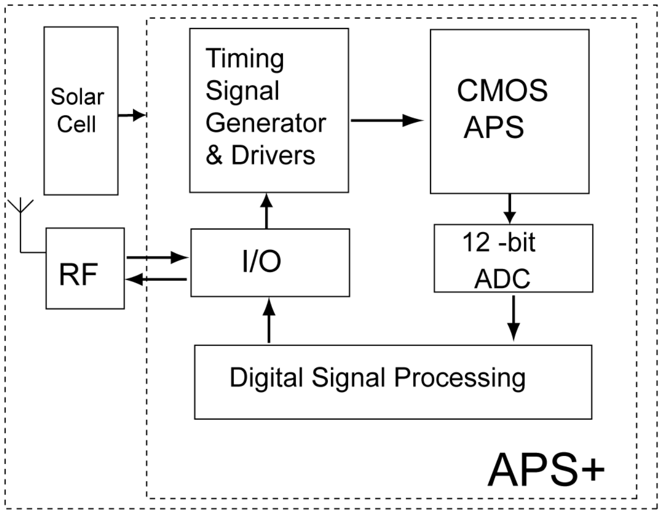

Fig. 2. Block diagram of the μDSS

radiation. Any radiation damages show up as single-pixel defects instead of column defects as it is the case of CCD imagers. Because of these advantages, CMOS image sensor APS is chosen for μDSS.

As illustrated in Fig. 3, the APS is composed of four blocks: pixel array (512×512), current mirror array, column sample-hold array, two address decoders (in column and row directions), and a chip level analog chain which processes the signals and generates the analog sensor output. [5] This architecture is almost the same as an ordinary 3-T APS image sensor. The only difference is that the APS of μDSS needs two address decoders, while an ordinary 3-T APS image sensor has only one row decoder. The extra column decoder in μDSS is used for windowing.

For an ordinary sun sensor, the detection of the sun spot is based on the readout data from all pixels in the pixel array. The typical procedure starts from the sun acquisition mode, when the pixel array is scanned from top left to top right and progressed line by line to the bottom right hand corner. In case five pixels are found which have intensities above the threshold intensity, these pixels are taken to be the sun. Then the sensor switches to a windowing mode for more precise centroid calculations. In this windowing mode, a 25×25 pixel window is put around the previously found position and the centroïd of the incident radiation is calculated.

In the μDSS application, the sun illuminates approximately 10×10 pixels of the pixel array. Thus it is a waste of time and power to readout every pixel in the array. In order to increase the detection speed and reduce power consumption, a two-folded acquisition-tracking mode is employed in the μDSS. During the acquisition mode, the rough location of the sun spot is decided [3] [4]. This rough location is the Region-of-Interest (ROI) for the next working stage. During the following tracking mode, the pixels within the ROI are readout. The accurate position of the sun spot is calculated based on the readout of the tracking mode.

A. *Acquisition Mode*

The APS starts working in an acquisition mode. The purpose of the acquisition mode is to decide a 21×21 pixel region which contains the complete sun spot (10×10 pixels plus elongation due to angle of incidence). This ROI is decided according to row and column profiling information of the pixel array. This is illustrated in Fig. 4.

The profiling is achieved by a specific pixel design "Winner-Takes-It-All (WTIA) [1] [2]". With this pixel architecture, at the end of integration time, pixels on the same column/ row are shorted. In this way, every column/row bus of the image sensor holds the information of the most heavily illuminated pixel (the "winner") on each particular column/ row respectively. In this way, the profile along column/ row-direction can be achieved (indicated by red lines in Fig. 3). The "winners" occupy the column/ row buses; this is the reason that the principle is called "Winner-Takes-It-All". During this working mode, profiles are achieved within readout time for two lines. Based on the profiling result, the digital signal processing circuit determines the ROI for the following tracking mode, which is 21×21 pixel region on the pixel array.

B. *Tracking Mode*

At the end of the acquisition mode, the 21×21 pixel ROI is identified by signal processing circuit. The APS will be switched into the sun tracking mode, in which it works in the same way as an ordinary 3T APS image sensor: every pixel is readout in the 21×21 sub-array. Compared with the "rough" readout results of the acquisition mode, the readout data are more accurate. The readout data in this mode will ultimately determine the accuracy of the complete sun sensor.

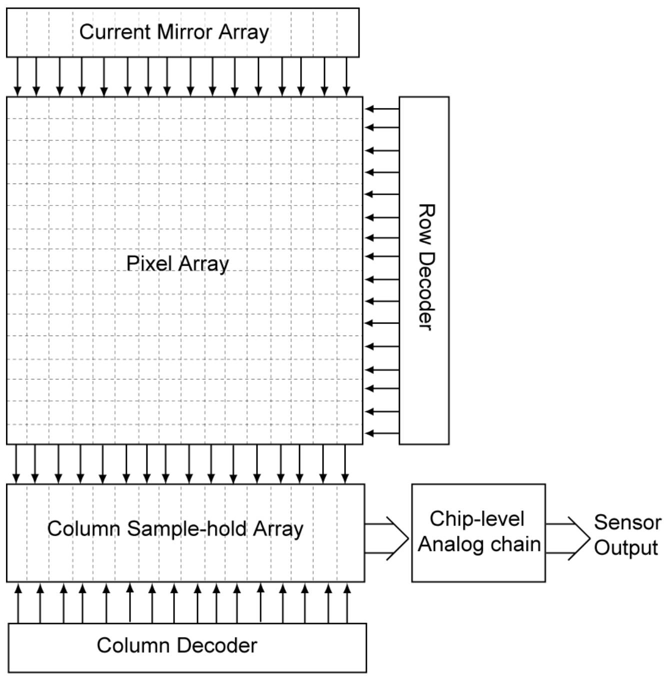

Fig. 3. Architecture of APS in μDSS

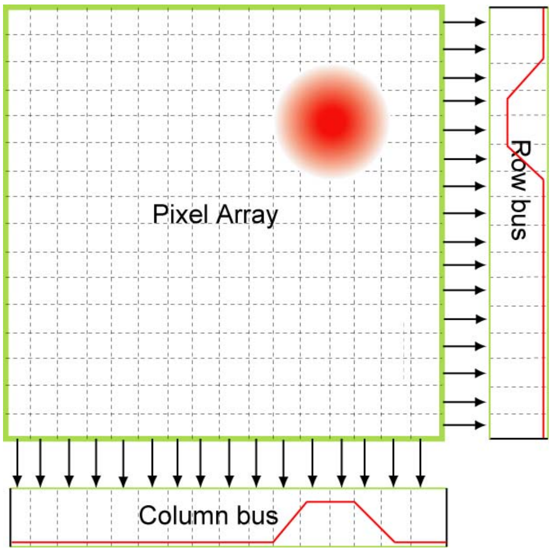

Fig. 4. Profiling on column and row bus

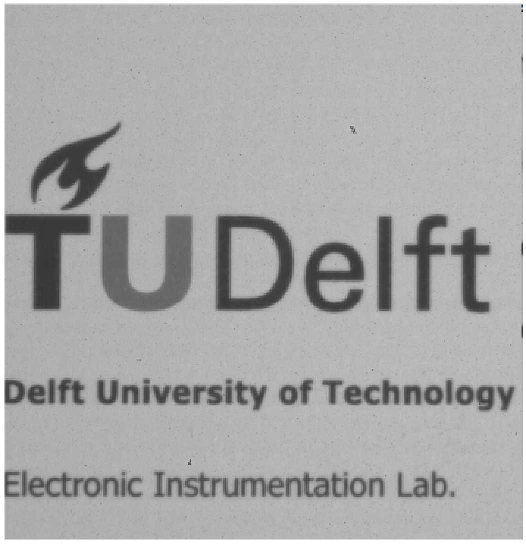

Fig. 6. An image captured by APS

By this acquisition- tracking mode operation, the uDSS can locate the sun spot's centre within the readout time for two lines (acquisition mode) plus 21×21 pixels (tracking mode). Therefore, compared with an ordinary sun sensor, the uDSS has a faster detection speed and lower power consumption.

C. *Measurement Results*

A first test chip has been realized in a standard 0.18µm CMOS process. On the test chip, APS has a pixel array of 368 x 368 pixels, pixel pitch is 6.5µm. The profiling results in the acquisition mode are illustrated in Fig. 5. In the measurement, the chip is illuminated by a DC light source, which emulates the sun light. The result demonstrates the directions. The x and y coordinate of the light spot's location is indicated by the peak of each curve.

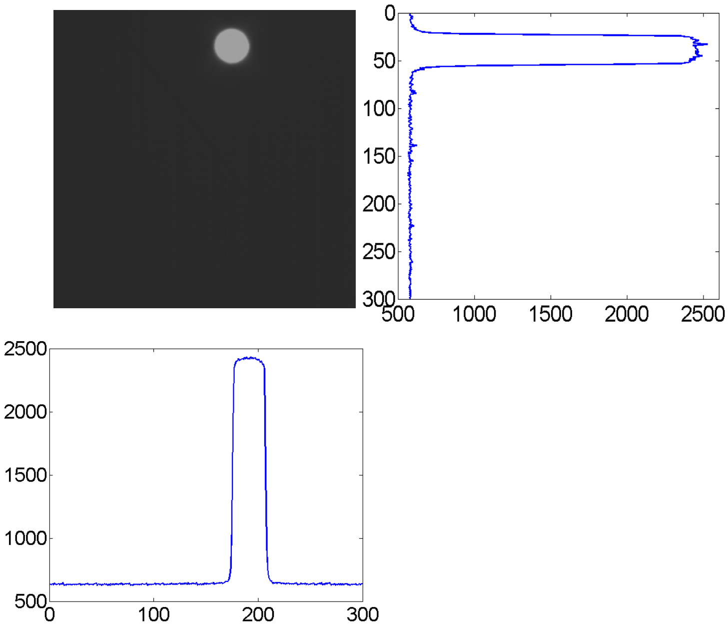

Fig. 5. Measurment results of acquisition mode

During the tracking mode, the APS works in the same way as an ordinary imager. Fig. 6 shows an image taken by the APS.

"Photon Transfer Curve" is a measurement tool which can be used to evaluate many parameters of an image sensor, including full well capacity (e-/pixel), conversion gain K (DN/e-), dynamic range, conversion factor CF (V/e-), etc. Fig. 7 illustrates this curve derived from APS. TABLE I shows the parameters achieved from this curve. From the curve, the full well capacity is 37,000e-/pixel. The filter deposited on the membrane pinhole must control the photon number reaching the pixel array, in order to avoid pixel being saturated. This means that about one percent of the light is passed through the pinhole filter. The fine tuning of the intensity can be performed by an integration time control of the digital processing circuit.

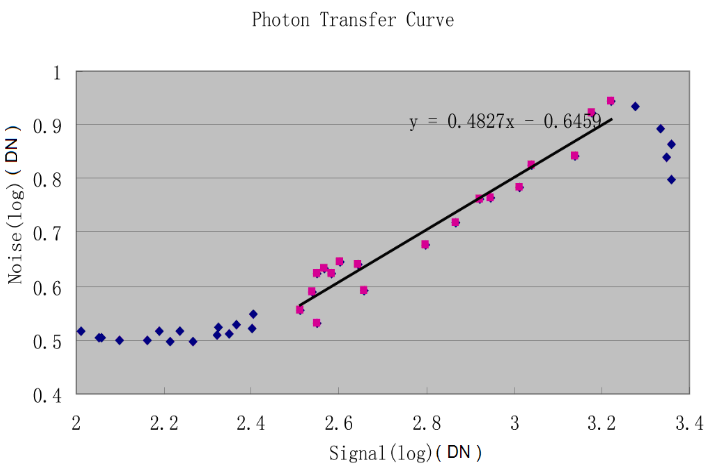

Fig. 7. Measurement of photon transfer curve

TABLE1. APS PARAMETERS

Full Well Capacity, Q (e-/pixel)	Conversion gain, K (DN/e-)	Pixel capacity, C (fF)	Conversion factor, CF (μV/e-)
37,000	0.045	5.3	30

III. DIGITAL SIGNAL PROCESSING

The digital signal processing part of the APS+ includes several functionalities. First of all during acquisition mode the sun position is determined by reading out the intensity of consecutive pixels. Once the sun position is found and a window positioned around the sun position is determined, the centroid of the incident radiation will be calculated.

The centroid calculation is in first onset straight forward, but a number of corrections have been applied. As space based imagers are exposed to significantly high levels of cosmic radiation, the mitigation of single event upsets has to be taken into account. As bright or dark pixels can also influence the centroiding accuracy, also for compensation of these effects digital signal processing is used.

Single event upsets (which generally lead to a bright spot in the image) are taken care of by checking the relative intensity of the pixel with respect to the neighboring pixels. As soon as the intensity of all neighboring pixels is above the threshold intensity and the intensity varies more then 25% from the average of the neighboring pixels the value is replaced by the average of the neighboring pixels.

This way both dark and bright pixels are compensated for. Although this will have a smoothening effect, tests on the conventional digital sun sensor from TNO have shown this principle to work to full satisfaction.

The actual centroid is calculated by looking at the slopes with intensity increase only as these slopes basically determine the centroid and as this will make the algorithm more robust to saturation of the peak signal and spot broadening due to the changing angle of incidence. (the spot at 64 degrees angle of incidence is about twice as long)

If for some reason no sun centroid can be calculated (upset outside of the imager for instance or wrong positioning of the window) the imager switches back to acquisition mode automatically.

IV. CONCLUSION

This paper describes the implementation and first test results of μDSS chip. The APS works in two stages: First, in the acquisition mode, the sun spot's location is roughly detected. Next, in the tracking mode, every pixel in the ROI, which was derived from the acquisition mode, is read out. Based on the result of the tracking mode, the final location of the sun spot is calculated by the signal processing circuit. Bearing features of fast speed and low power consumption, the μDSS makes itself ideally suitable for sun sensing applications.

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