Electro-optical Characterisation of a Complementary Metal-Oxide Semiconductor Image Sensor for Optical Imaging Application

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Abstract. Advances in Complementary Metal Oxide Semiconductor (CMOS) Active Pixel Sensor (APS) technology has many potentials for application in optical imaging techniques. CMOS APS offers high speed read out and on-chip signal processing not available from the predecessor technology, charge couple device (CCD). Performance of a commercial ON Semiconductor's CMOS, MT9J003 was characterised for application in 3D optical imaging system. This work focuses on the electro-optical performance of the sensor. Two techniques were used, the mean-variance and the photon transfer to determine the sensor conversion gain, the noise and the dynamic range of the sensor. Images at different LED illumination levels were captured by the sensor to obtain the relationship between the mean signal and the noise from the images using in-house computer programme developed with LabVIEW (National Instruments, Austin, TX). Photon transfer technique allows separation of the shot noise in the sensor from the other types of noises that are inseparable using mean-variance. Mean-variance underestimates the conversion gain of the CMOS. Results indicate that the photon transfer provides a more accurate estimation of the electro-optical performance of a CMOS APS.

Keywords: CMOS image sensor, photon transfer technique, mean-variance technique

I. INTRODUCTION

Complementary Metal Oxide Semiconductor (CMOS) Active Pixel Sensor (APS) is now widely used in optical imaging because of the low power consumption, small size, on-chip functionality and high-speed imaging compared to the predecessor technology, charge-coupled devices (CCD) [1]. Optical computed tomography (CT) system is an imaging technique that may benefit from advances in CMOS APS. The imaging technique is an optical equivalent to x-ray CT scanning for sample that is optically translucent. One of the application is for measurement of radiotherapy dose imparted in a 3D radiochromic dosimeter [2,3]. The optically transparent dosimeter will gradually become opaque after it is exposed to the radiation through polymerisation of the material. The optical densities of the material increase with absorbed dose. The irradiated dosimeter is scanned by the optical CT to measure the absorbed dose from radiotherapy [4,5,6].

Before an image sensor can be applied in an imaging system, the performance of the sensor should be fully evaluated. The performance varies between production batches during manufacturing [7]. Each sensor has to be characterised to determine the sensor's performance and the suitability of the sensor for the intended application [8]. The performance parameters of interest in this study are read noise, dark current, shot noise, conversion gain, full well capacity and dynamic range, measured using the mean-variance and the photon transfer technique.

II. MATERIALS AND METHODS

A. Experimental Setup

The CMOS APS was set up in a dark room as shown in Figure 1. A neutral density filter with 1.0 optical density (OD) was placed in front of the sensor to reduce the intensity of the light that enters the CMOS APS and positioned at distance D, 70 cm from a 630 nm LED (TMS Lite, Penang, Malaysia). It is a large array LED with the size of 10.2 cm width and 10.4 cm height. The LED was connected to a light intensity controller to vary the intensity of the LED by changing the current supplied. The camera was connected to a PC using USB 3.0 and controlled by LabVIEW (National Instrument, Austin, TX).

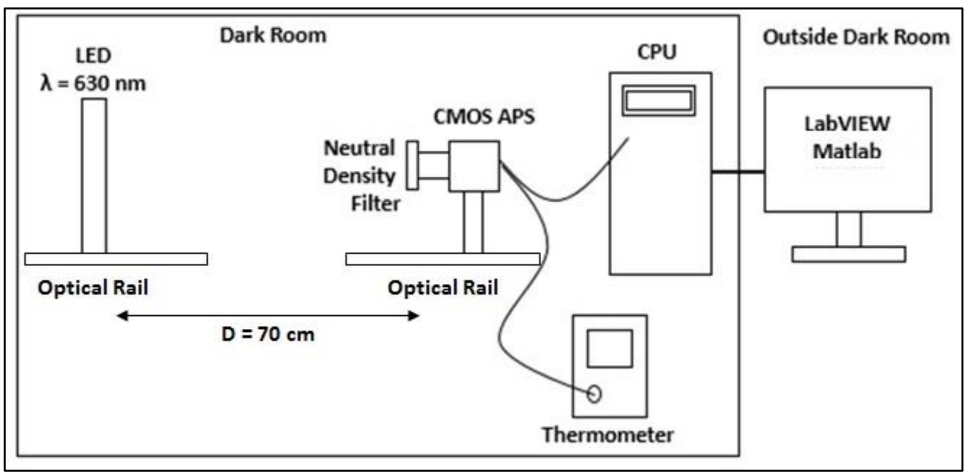

FIGURE 1. Experimental setup for characterisation of the CMOS sensor

B. Characterisation of Dark Signal

The sensor was placed in a dark room and connected to the PC. The LED was switched off and the thermometer was connected to the sensor with the lens capped. This experiment was performed without sensor cooling to investigate the sensor performance at the room temperature. The images were captured at several exposure time between 0.035 ms to 71.015 ms and analysed using Matlab (Mathworks, Nattick, MA). The mean and standard deviation of the pixel values in the images were measured.

C. Characterisation of Electro-optical of Performance Parameters

Electro-optical characterisation requires images from the sensor at different LED illumination intensity to obtain the relationship between the mean signal and the noise from the images. The amount of light collected by the sensor was controlled using two methods. The first method makes use of the variation in the LED brightness of 80 levels of intensity, exposed to the sensor at a constant exposure time. The second method makes use of the variation in the sensor exposure time between 0.035 ms to 50 ms, illuminated with the LED of constant intensity. For each method, a series of images were captured at variable light exposure, and the mean, variance and standard deviation of pixels value in Digital Number (DN) were calculated.

The relationship between mean signal (S_m), signal variance (σ^2_S) and read noise (σ^2_{Read}) for the mean-variance analysis were calculated using equation from Holdsworth *et al.* (1990). The sensor conversion gain was obtained using photon transfer technique by applying equations from Bohndiek *et al.* (2008) [8]. The read noise, shot noise, full well capacity and dynamic range were calculated using the estimated conversion gain. Details on the techniques and analysis of the sensor performance parameters have been explained in previous works [8-12].

III. RESULTS AND DISCUSSION

A. Dark Signal

The average value of the dark signal at exposure time between 0.035 ms to 71.015 ms was 320.07 DN with standard deviation of 0.07 DN. The temperature of the sensor was maintained in the range of 45°C to 46.2°C. The dark signal is flat with integration time at the measured range of sensor temperature. The sensor is suitable to operate without cooling at room temperature.

B. Electro-optical Performance

Figure 2 shows the mean-variance plots from the two different methods, variation in the LED intensity and variation in the sensor exposure time. Each plot displays two linear regions before the saturation; at low-level signal (<800DN) and at the high-level signal (≥1200DN to 3500DN).

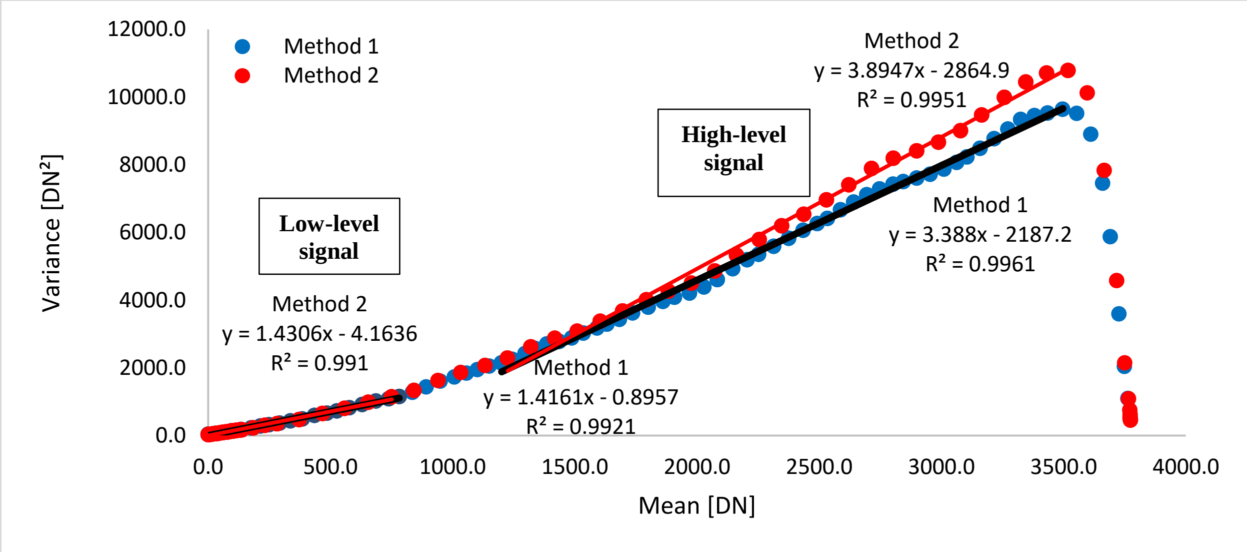

FIGURE 2. Mean-variance graph for method 1 and method 2

At both linear regions, the conversion gain was calculated. The read noise was measured using low signal gain, multiplying it with a square root of the variance at the dark level or the value of the intercept-y of the graph. However, to measure the full well capacity (FWC), the high signal conversion gain is used. Using read noise σ_{Read} and full well capacity, the dynamic range (DR) was obtained. All calculated sensor parameters for mean-variance analysis were summarised in Table 1.

TABLE 1. Comparison values between photon transfer and mean-variance for method 1 and method 2

	Mean-Variance		**Photon Transfer**	
Parameter	**Method 1**	**Method 2**	**Method 1**	**Method 2**
Conversion gain (e^-/DN)	0.71±0.03 (K_{low}) 0.30±0.03(K_{high})	0.70±0.02 (K_{low}) 0.26±0.06 (K_{high})	1.95±0.01	2.01±0.01
Read Noise (DN)	5.68±0.01	4.94±0.01	6.82±0.01	6.61±0.01
Read Noise (e^-)	4.03±0.20	3.46±0.10	13.29±0.07	13.28±0.07
S_{max} (DN)	3497.0	3519.5	3324.9	3346.3
Full Well Capacity (e^-)	1049.10±0.03	915.07±0.06	6483.56±0.01	6726.06±0.01
Dynamic Range (dB)	48.31±0.4	48.45±0.3	53.77±0.05	54.09±0.05

The photon transfer curve obtained using method 1 and method 2 are shown in Figure 3. The read noise component was separated from the photon transfer curve. A linear fit line to the shot noise curve exhibits a slope of 0.49 between 4 DN and 3300 DN. Using the gradient of the graph, the conversion gain was calculated. Read noise σ_{Read} was derived by averaging the mean signal before CMOS APS detected the light and multiplying it with the conversion gain. Full well capacity (FWC) was measured by multiplying maximum signal with the conversion gain and the dynamic range (DR) was determined from the full well capacity (FWC) and read noise σ_{Read} where DR = 20 log (FWC/σ_{Read}). The sensor parameters for the photon transfer curve were tabulated in Table 1.

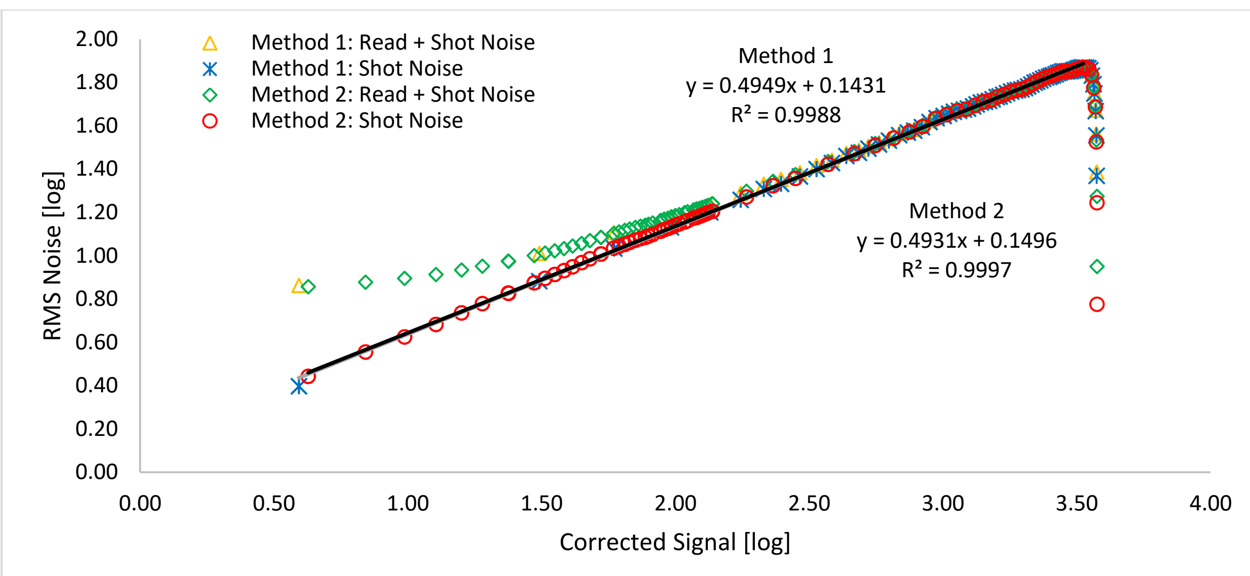

FIGURE 3. Read and shot noise photon transfer curve for method 1 and method 2

C. Comparison between Mean-Variance and Photon Transfer Results

The sensor performance parameters for method 1 and method 2 are summarised in Table 1. The signal conversion gain obtained from the mean-variance is lower than photon transfer technique. The gain will influence the read noise, full well capacity and dynamic range expressed in physical terms (e^-) calculated using the gain value. Bohndiek *et al.* (2008) also has reported that the mean-variance analysis underestimates the sensor conversion gain with 8% differences in comparison with PTC.

IV. CONCLUSION

The work shows that mean-variance underestimates the conversion gain of a CMOS APS and thus affecting the value of read noise, full well capacity and dynamic range. Photon transfer technique provides more accurate estimation since the gain were estimated by removing other sources of noise except the shot noise. The sensor has low read noise (about 13 e^- at operating temperature of 45^oC – 47^oC) and high saturation point of 3346 DN without temperature control of the sensor. The dynamic range of the CMOS derived using photon transfer is 54 dB.

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