Overcoming the Full Well Capacity Limit: High Dynamic Range Imaging Using Multi-Bit Temporal Oversampling and Conditional Reset

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***Abstract*— We describe a high dynamic range image sensor that oversamples the incident light in time by using the ADC output at each sampling as part of the final response and resetting the pixel only if a threshold has been exceeded. We show that such multi-bit sampling at each time step is equivalent to spatial oversampling with virtual binary pixels (jots) whose thresholds correspond to the steps of the ADC. Threshold selection and sampling intervals of variable duration are used to optimize the response. The dynamic range of such an image sensor is not limited by the full well capacity but by the sampling policy, i.e. the choice of when and how to sample. Such an image sensor can be built based on current pixel technologies. Initial experimental results from a test chip demonstrate dynamic range extension by a factor of 14 compared to a conventional sensor in the same technology.**

I. Introduction

In the last decade CMOS image sensors replaced both photographic film and CCD image sensors in most markets. The use of CMOS technology made Moore's law scaling of pixel sizes possible. However small pixels have low dynamic range as their full well capacity is restricted by the pixel size.

To overcome this limitation and to extend sensor dynamic range, Eric Fossum [1], [3] and Luciano Sbaiz et al. [2] proposed using very small pixels to oversample incident light in space and / or time, making a binary decision at each sampling by comparing the detected photons against a threshold. The total number of photons in the exposure can then be reconstructed from the results (0 or 1) of these binary samplings. Feng Yang et al. [4] derived the theoretical limits of such binary oversampling based on photon statistics. Both proposals assumed samplings equidistant in time and pixel reset after each sampling. They require a very small pixel with close to single photon sensing characteristics. In the remainder of this paper we will follow [3] by naming the binary sampled element "jot", reserving "pixel" for the aggregate that is used to form the final image.

Prior work by Thomas Vogelsang and David G. Stork [5] showed that binary sampling can be done with less-sensitive pixels and dynamic range can be extended well beyond the dynamic range achieved by the binary approach of Fossum and Sbaiz if pixels are reset only when they are sampled above the threshold (conditional reset) and when the duration of sampling intervals is varied. Conditional reset utilizes the full exposure time to collect light at very low light levels and variable duration of sample intervals provides very short intervals to sample high light intensities without increasing the number of intervals.

In the work presented here we expand this approach to multi-bit oversampling. We show that multi-bit oversampling is mathematically equivalent to binary oversampling with virtual jots. Multi-bit oversampling with conditional reset allows extending the dynamic range of small pixels used in current mobile image capture systems by 10x or more since the dynamic range is no longer limited by the full well capacity but by the sampling policy, i.e. the choice of when and how to sample.

After presenting the theoretical background we compare the modeled sensor response to hardware results of a small test chip before we state our conclusions.

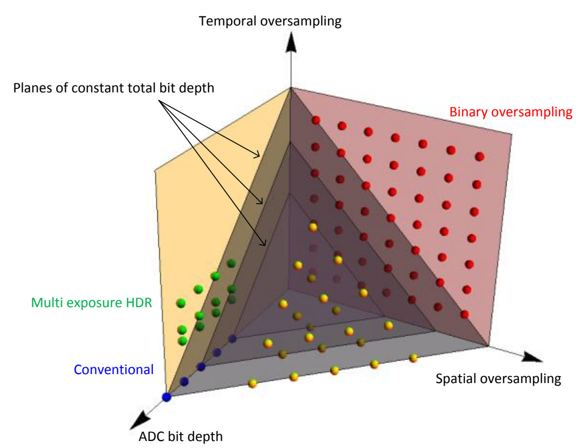

Fig. 1: Image sensor design space

II. Modeling of Sensor Response

Each pixel of a conventional image sensor samples the pixel only once at the end of the exposure, deriving its resolution from the bit depth of the ADC. The proposed binary pixel sensors on the other hand derive their resolution from temporal or spatial oversampling. The total image sensor design space can therefore be viewed as a three-dimensional space with the bit depth of the ADC and the amount of temporal and spatial oversampling as the axes. The measurement of the incident light comes from the total bit depth. Fig. 1 illustrates this concept and shows planes of total bit depth as well as the design space used by different sensors. The dynamic range of conventional sensors comes from ADC bit depth only. Binary oversampling image sensors lie on the plane defined by the axes of spatial and temporal oversampling. Multi-exposure high dynamic range (HDR) derives most of its resolution through ADC bit depth but has some temporal oversampling (unconditional or hard reset between samples). Our theory accurately models all combinations of temporal and spatial oversampling as well as ADC bit depth.

The equivalence between binary oversampling and multi-bit oversampling can be shown by examining the probabilities of the ADC to return a specific data number. We show this in Table I using the example of a very small pixel that saturates at 21 photons and is sampled with an ADC with 3-bit resolution. The ADC has then an output (data number d) from 0 to 7 depending on the light intensity. The probability to return data number d is the probability to sample a charge corresponding to data number d or higher minus the probability to sample a charge corresponding to data number $d+1$ or higher. The expected data number at a given light intensity is the sum of these probabilities multiplied with the data numbers associated with them. Rearranging the terms of the equation demonstrates that the expected data number of a multi-bit sensor is the same as of a binary pixel sensor combining the result of jots with thresholds set to the different possible ADC outputs.

Table I: Example of probabilities and thresholds

Incident light	Threshold θ	Data number d	Probability of θ reached or exceeded	Probability to return d
21 and above	21	7	$P_7 = Pr[y \geq 21]$	P_7
18 to 20	18	6	$P_6 = Pr[y \geq 18]$	$P_6 - P_7$
15 to 17	15	5	$P_5 = Pr[y \geq 15]$	$P_5 - P_6$
12 to 14	12	4	$P_4 = Pr[y \geq 12]$	$P_4 - P_5$
9 to 11	9	3	$P_3 = Pr[y \geq 9]$	$P_3 - P_4$
6 to 8	6	2	$P_2 = Pr[y \geq 6]$	$P_2 - P_3$
3 to 5	3	1	$P_1 = Pr[y \geq 3]$	$P_1 - P_2$
0 to 2		0		

$$\text{Expected data number} =$$
$$1 \cdot (P_1 - P_2) + 2 \cdot (P_2 - P_3) + 3 \cdot (P_3 - P_4) + 4 \cdot (P_4 - P_5) + 5 \cdot (P_5 - P_6) + 6 \cdot (P_6 - P_7) + 7 \cdot P_7 =$$
$$P_1 + P_2 \cdot (2-1) + P_3 \cdot (3-2) + P_4 \cdot (4-3) + P_5 \cdot (5-4) + P_6 \cdot (6-5) + P_7 \cdot (7-6) =$$
$$P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 =$$
$$\text{Response of binary sensor}$$

More generally, assuming n_B virtual jots with thresholds at multiples of the ADC step size d_m in sampling interval m one can set the threshold $\theta_{i,m}$ of the i-th virtual jot to

$$\theta_{i,m} = i \cdot d_m.$$

The expected response is then the sum of each data number multiplied with its probability

$$\mathbb{E}(y) = \sum_{i=1}^{n_B} i\left[p_{i,m}\left(\lambda_{i,m}, \theta_{i,m}\right) - p_{i,m}\left(\lambda_{i,m}, \theta_{i+1,m}\right)\right].$$

This equation can be transformed to the response of the binary oversampling sensor derived in [5]

$$\mathbb{E}(y) = \sum_{i=1}^{n_B} p_{i,m}\left(\lambda_{i,m}, \theta_{i,m}\right).$$

There are however important differences between virtual and real jots that need to be considered. Real jots need to be placed in different spatial positions, while the virtual jots of the multi-bit sampling all occupy the area of the real pixel, so virtual jots are larger than real jots for a given pixel size (Fig. 2).

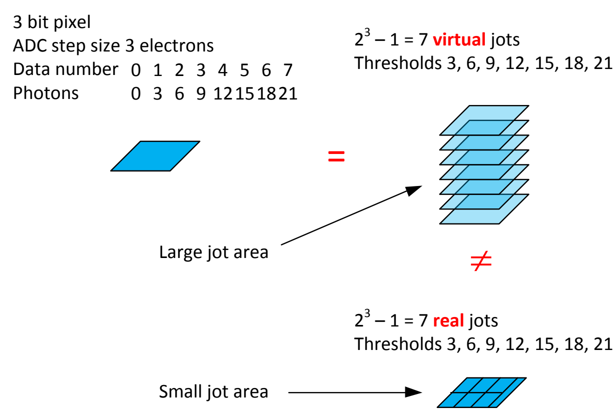

Fig. 2: Virtual and real jots

Because the virtual jot has a larger photo-active area, a multi-bit oversampled image sensor will have better low-light sensitivity than a spatially oversampled binary image sensor unless the latter has real jots that are more light-sensitive by a factor that compensates for the area reduction. Also, either all or none of the virtual jots that correspond to a pixel have to be reset while a pixel using real jots and conditional reset would reset the jots above the threshold but not below the threshold. When using the equations of [5], a common reset threshold $\theta_{rst,m}$ has to be used when calculating reset probabilities. To calculate the final pixel response, ADC results are captured and summed up when the ADC is above the threshold and at a final residue read at the end of the exposure. The expected pixel response becomes then

$$\mathbb{E}(Y) = \sum_{i=1}^{n_B} \sum_{m=1}^{N-1} \frac{p_{\theta_{rst,m}}}{p_{1,m}} p_{i,m} + \sum_{i=1}^{n_B} p_{i,N}.$$

Figures 3 (unconditional reset) and 4 (conditional reset) compare the different approaches. Lines denote the result of calculation using the analytical model; asterisks denote Monte Carlo simulation. In all cases the total bit depth is 8 and the examples with temporal oversampling have variable sampling interval duration with the longest interval 128 times longer than the shortest to extend the dynamic range without increasing the total bit depth. The black curve is the response of a conventional sensor with an 8 bit ADC and 20 electrons per data number saturating at 5100 electrons. The other curves are oversampling sensors, adding the result of the individual samplings.

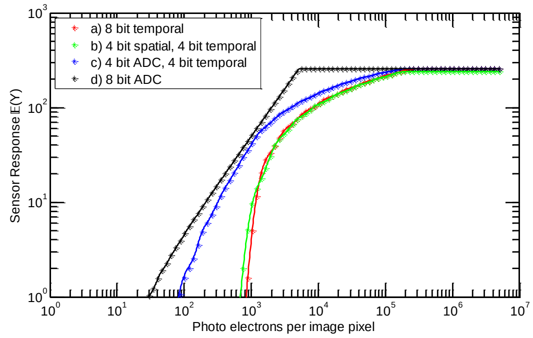

Fig. 3: Sampling policies without conditional reset

Red and green curves are binary oversampling sensors with a threshold of 20 electrons. The red curve is of a sensor that oversamples only in time (256 times), while the green curve oversamples both in space (16 jots) and time (16 times). The blue curve is a sensor oversampling in time (16 times) with a 4-bit ADC. All sampling policies reset the pixel after each sampling. Without conditional reset, binary temporal and mixed temporal and spatial oversampling is equivalent (red and green curves in Fig. 3). The low-light sensitivity of the binary pixel without conditional reset is much worse than the conventional (black curve) approach since the number of photons per jot and sampling interval is lower. The multi-bit temporal oversampled pixel (blue curve) has improved low-light sensitivity since the spatial oversampling is less.

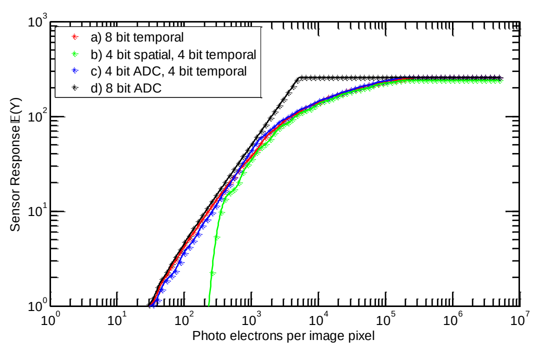

Fig. 4: Sampling policies with conditional reset

Fig. 4 shows the improved low-light sensitivity when conditional reset is used. The colors of the different curves correspond to the same sampling policies as in Fig. 3. Different from Fig. 3, pixels are reset only if they are sampled at or above the threshold (binary oversampled red and green curves) or if the data number returned by the ADC is not zero (multi-bit oversampled blue curve). The only curve that shows reduced low light sensitivity corresponds to the approach with spatial oversampling (green curve). The temporally oversampled approaches keep the extended dynamic range. In this example the dynamic range is extended by a factor of 20 compared to a conventional sensor, corresponding to an increase of effective full well capacity from 5,100 electrons to over 100,000.

III. EXPERIMENTAL RESULTS

Table II gives the basic parameters of our test chip. The pixel is based on a conventional pixel with an additional transistor to provide column in addition to row control of reset. Test results are given for two different pixel designs, one based on a 3T pixel with a partially pinned photo diode (Figs. 5 and 6) and the other for a 4T based pixel with a fully pinned photo diode (Figs. 7 and 8).

Table II: Sensor parameters

Technology	180nm CMOS Image Sensor
Pixel	3.6µm pitch, 3T based, partially pinned (Figs. 5 and 6) 7.2µm pitch, 4T based, pinned (Figs. 7 and 8)
Conversion gain	26 µV / e^- (3T), 83.4 µV / e^- (4T)
ADC	10 bit
Sensor size	64·64 pixels

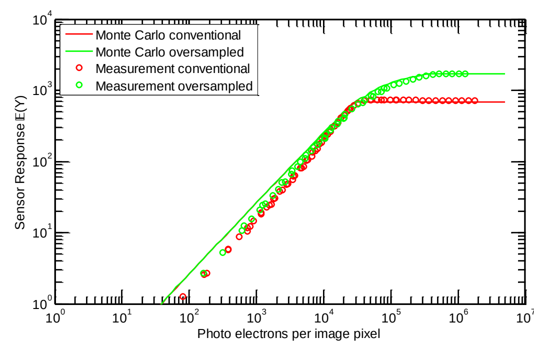

Fig. 5: Response curve model against hardware (3T based pixel with partially pinned photo diode)

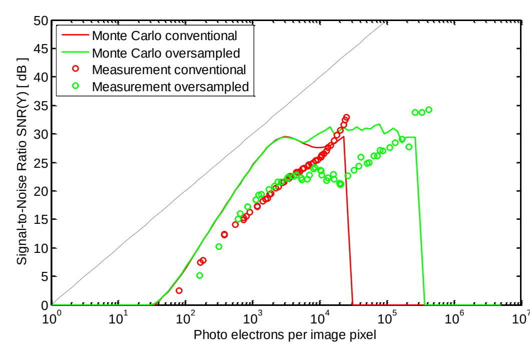

Fig. 6: Signal-to-noise ratio model against hardware (3T based pixel with partially pinned photo diode)

We are showing two different sampling policies with the two different pixel types. The choice of sampling policy is not dependent on the pixel type; we could as well have swapped the policies or tested different ones with either pixel type. In both cases we used conditional reset.

When testing the sensor with the 3T based pixel we used a sampling policy where we oversampled 8 times at an ADC bit depth of 8 for a total bit depth of 11. The ratio of the longest to shortest interval was 15 and the ratio of the total exposure to the shortest exposure was 42. The reset threshold θ_{rst} was 110DN.

The oversampled sensor is denoted by the green curves (simulation) and circles (measurement), the conventional sensor is denoted by the red curves and symbols. The conventional comparison has been done with a 10-bit ADC. The dynamic range with this choice of oversampling has been extended by 22dB or a factor of 13, from 58dB to 80dB measured at an SNR of 0dB and from 33dB to 55dB measured at an SNR of 20dB. Figs. 5 and 6 show the measured and simulated sensor response and signal-to-noise ratio. The agreement of the response curve and the range of the SNR curve between model and hardware is very good. There are some deviations in the shape of the SNR curve which are likely due to incomplete modeling of all hardware noise contributors, especially the lag that occurs in a 3T pixel with an only partially pinned photodiode.

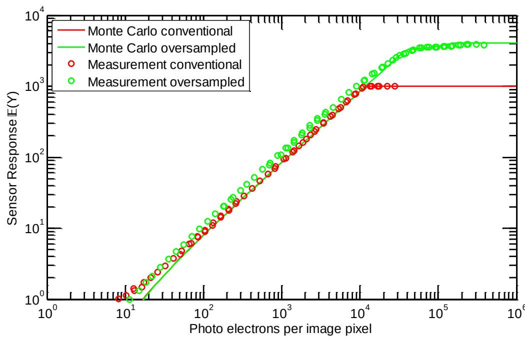

Fig. 7: Response curve model against hardware (4T based pixel with pinned photo diode)

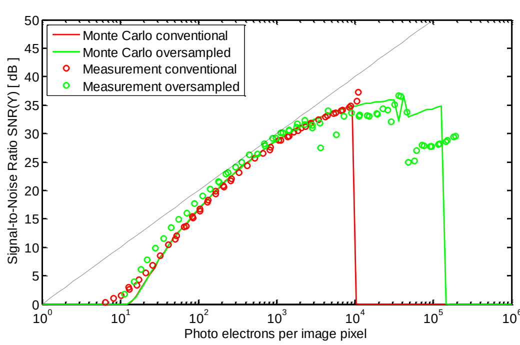

Fig. 8: Signal-to-noise ratio model against hardware (4T based pixel with pinned photo diode)

When testing the sensor with a 4T based pixel we used a sampling policy where we oversampled 4 times at an ADC bit depth of 10 for a total bit depth of 12. The ratio of the shortest to the longest interval was 4 and the ratio of the total exposure to the shortest exposure was 13. The reset threshold θ_{rst} was 180DN. The oversampled sensor is denoted by the green curves (simulation) and circles (measurement), the conventional sensor is denoted by the red curves and symbols. The conventional comparison has been done with a 10-bit ADC. The dynamic range with this choice of oversampling has been extended by 23dB or a factor of 14, from 59dB to 82dB measured at an SNR of 0dB and from 35dB to 58dB measured at an SNR of 20dB. Figs. 7 and 8 show the measured and simulated sensor response and signal-to-noise ratio. The agreement of the response curve and the range of the SNR curve of the oversampled measurement between model and hardware is very good. The root cause of the deviation in the shape of the SNR curve at the high end of the dynamic range is currently under investigation.

IV. Conclusion

We have shown that multi-bit temporal oversampling with conditional reset and variable duration of sampling intervals can be used to increase the dynamic range of image sensors by effectively extending the full well capacity. Conditional reset is necessary for good low-light sensitivity. A test chip was fabricated to implement the method, and the improvement in performance of 22dB in the case of the 3T based pixel and 23dB in the case of the 4T based pixel matches the simulation model. Our approach of pre-defined sampling intervals and conditional reset gives each pixel the optimal sampling sequence based on its light intensity without the need to add storage or decision circuits to each pixel. Since our measurements and model agree, we predict that we can achieve over 80dB dynamic range in a single shot capture with a 1.4um pixel.

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References

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