

Dual Linescan Architecture for High Responsivity and Low Photon Shot Noise

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Motivation

Successive generations of machine vision systems operate with increasingly higher speed. Historically, the increase in speed has to be matched by an equivalent increase in responsivity (see Figure 1). This is because many high-speed scanning applications are photon starved. The use of brighter sources of illumination is often not an option, since this increases system cost. In some cases, brighter illumination can also result in a safety hazard.

With conventional linescan architectures, higher responsivity leads to fewer signal electrons. Fewer signal electrons in turn lead to higher photon shot noise. Indeed, photon shot noise has been increasing with successive generations of linescan cameras, as illustrated in Figure 2. If this trend continues, the level of photon shot noise will soon exceed the level acceptable for many machine vision applications. We currently present a linescan architecture that breaks this trend.

Increasing the responsivity of conventional linescan cameras also leads to a higher noise floor, unless the following two conditions can be met: (1) The increase in responsivity is matched by an equivalent increase in sensor charge conversion efficiency (CCE), and (2) New generations of higher speed amplifiers have the same noise levels as earlier amplifiers. Reset noise can be ignored since reset noise can be removed using correlated double sampling.

Satisfying these two conditions is not an easy task. We have managed to significantly increase the CCE with each successive generation of linescan sensors. However, an even greater rate of increase is required. We have also succeeded in reducing amplifier noise even with the increase in amplifier bandwidths, but not at the rate required to keep the camera noise floor constant. If current trend continues, the camera noise floor will soon exceed the digital detection threshold of many machine vision applications. As shown in Figure 3, the linescan architecture that we are currently presenting breaks this trend.

Dual Linescan Architecture

We present a novel linescan architecture that doubles the number of signal electrons collected. The schematic of the architecture is shown in Figure 4. The architecture consists of two parallel arrays of pixels. Each pixel is connected to a selectable delay gate that either allows charges through or delays the charges by one scan line. Signal electrons from the two arrays – one delayed and one not – are then internally combined into a single output.

The architecture is functionally equivalent to a 2-stage time-delay-and-integration (TDI) sensor. Unlike a TDI however, there is no polysilicon gate over the photosensitive area to degrade the blue and UV response. Focusing issues normally associated with TDIs are not present. Unlike TDI sensors, exposure control is also available.

The delay needs to be selectable to permit bidirectional scanning. If the image of the object scanned is moving from the top to the bottom of the sensor, the top array receives signals one line prior to the bottom array. To match the signals from the two arrays, signals from the top array are delayed. If the image is moving in the opposite direction, signals from the bottom array are delayed.

The operation of the selectable delay gate is shown in Figure 5. If no delay is needed, the sequence shown in Figure 5 is used. If delay is required, the transfer gate is pulsed prior to the delay gate (stage 3 is applied prior to stage 2). This stores signal charges temporarily in the delay gates awaiting the next transfer.

The main disadvantage of this architecture appears to be the $> 2x$ increase in dark signal. For high-speed applications however, the integration time is sufficiently short that the dark signal remains negligible.

Another drawback is the difficulty of incorporating more than two outputs. An alternative is to use separate outputs for the top and bottom arrays. Signals from the two arrays can then be averaged off-chip. The signal-to-noise ratio (SNR) of this approach will still be better than a conventional linescan, but not as good as combining the signals on-chip. An on-chip merge increases SNR by a factor of 2, while off-chip averaging increases the SNR only by $\sqrt{2}$.

At first glance, it appears that the CCD capacitance (and hence the power dissipation) is twice that of a conventional linescan. Each of the two CCD readout registers only needs to handle half the amount of signal charges however, so the CCD capacitance will not quite double that of a conventional linescan.

Device Performance

Measured specifications are listed in table 1.

Conclusion

We present a dual linescan architecture that has twice the responsivity and twice the dynamic range of a conventional linescan sensor. For light-starved applications, the signal to photon shot noise ratio also improves by a factor $\sqrt{2}$.

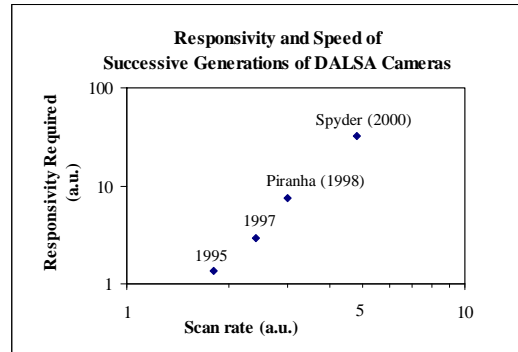


Figure 1. Responsivity and speed of successive generations of DALSA linescan cameras.

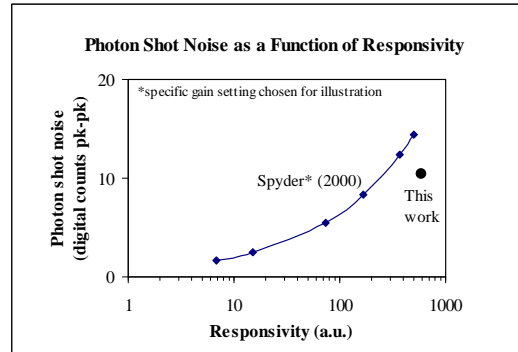


Figure 2. Photon shot noise as a function of camera responsivity.

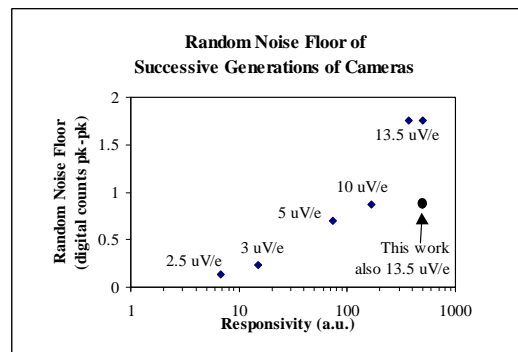


Figure 3. Random noise floor of successive generations of cameras.

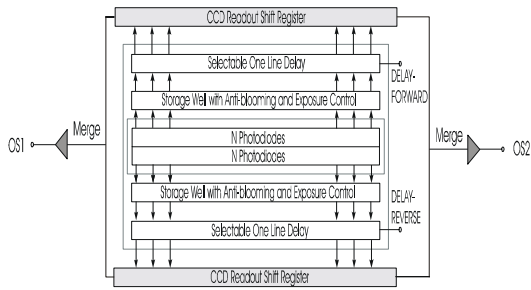


Figure 4. Dual linescan architecture schematic.

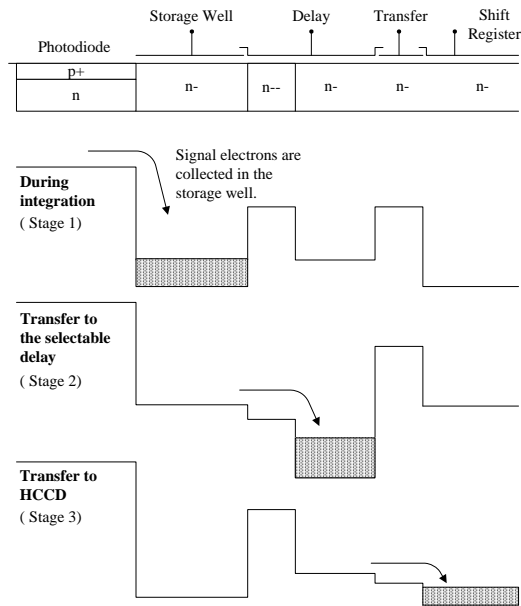


Figure 5. Potential well diagram of charge transfer in the pixel.

Table 1. Device performance.

Specification	Value	Comment
Peak responsivity	127 V/($\mu\text{J}/\text{cm}^2$)	700 nm
UV responsivity	27 V/($\mu\text{J}/\text{cm}^2$)	250 nm
Charge conversion efficiency	13.5 $\mu\text{V}/\text{e}$	At the sensor output
Data rate (with CDS)	40 MHz x 2 outputs	Waveform shape acceptable for CDS
Data rate (no CDS)	60 MHz x 2 outputs	CDS is difficult
CTE	> 0.99998	
Saturation output	750 mV	Antiblooming guaranteed
Full well	55 ke-	
rms noise at dark (no CDS)	48 e- rms	Measured
rms noise at dark (with CDS)	30 e- rms	40 MHz CDS
Noise equivalent exposure	3.2 pJ/cm ²	40 MHz CDS, 700 nm
Saturation equivalent exposure	5.9 nJ/cm ²	700 nm
Pixel size	14 μm	Standard, Smaller pitch available
Exposure control	Available	No non-uniformity introduced
Antiblooming	100 x	
Fixed pattern noise (FPN)	< 40 e-	Maximum line rate
Photoresponse Non- uniformity (PRNU)	5% of signal	Typical
Delay and transfer clock pulse width	200 ns	Minimum
Bidirectional	Yes	
Pixel to shift register crosstalk	< measurement limit	Maximum data rate