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Application Note | Case Study | **Technology Feature** | White Paper

High speed low light imaging: escaping the shot noise limit

Noise is an important topic for all machine vision applications, especially if the requirements on image quality and speed are high and light levels are low. Changing parameters usually leads to an increase in noise. Bucking this trend, a novel dual-linescan architecture provides a way to preserve higher signal-to-noise ratio.

Machine vision applications constantly present sensor and camera designers with conflicting goals: higher resolution (to detect smaller features), higher speed (for faster inspection), higher sensitivity (for shorter exposures with less light), and lower noise (for better image quality). Nowhere are these demands stronger than in linescan applications, almost all of which have become high-speed low-light challenges. Conventional linescan designs are now approaching fundamental limits. In high-speed, low-light situations, photon shot noise, which depends on the number of photons detected rather than the electrons they generate, is becoming a limiter to image quality.

The challenge: more signal with less noise

Machine vision performance requirements always increase. Over the last decade, feature sizes (and critical defect sizes) in semiconductor wafer inspection (the largest MV application by dollar volume) have shrunk by a factor of 3.3 in each dimension (and therefore ~10.8x overall). At the same time, the area of wafers has grown by a factor of 2.25 as the industry moved from 200 mm to 300 mm lines, while wafer throughputs in wafers per hour have remained the same. As a result, the resolution demands have increased by an order of magnitude, while the throughput demands have more than doubled. Measured as the product of speed and resolution, performance has increased by roughly a factor of 25.

While this progression is not as dramatic as the advance of PC power from 1996's 90 MHz Pentium chips to 2006's 3.4+ GHz 64-bit processors, imaging engineers can still feel justifiable pride. Whether designers can make similar improvements in the next 10 years remains to be seen. Imaging performance is ultimately limited by analog operations, and machine vision applications present divergent goals that will press against fundamental limits of physics.

Higher resolution. As mentioned, inspection applications demand ever-greater resolution to detect smaller features with greater clarity. To make use of existing, economical lenses, pixels must be smaller to fit more of them into a given lens's imaging circle. Smaller pixels come at a price; they have less total area to collect photons, which limits the signal they can collect.

Higher scan rates. The need for speed is clear in machine vision. Faster inspection enables increased inspection system efficiency. Sensor designers have worked hard to deliver steady progress in pixel rates and amplifier bandwidth for greater speed. But higher speed often means higher noise, so image sensor designers have also worked hard to limit noise in their high-bandwidth amplifiers. Progress has again been steady, but not enough to keep the noise floor constant.

Less light. Higher scan rates reduce the time available to capture photons. With less time to collect the light applications need either higher light intensity or higher pixel sensitivity. Extremely intense light sources bring their own challenges—they deliver more photons, but they raise system cost, and not only can they damage the objects being inspected, they can even pose safety hazards. With each increase in speed, sensor designers have had to try to increase sensitivity.

Higher sensitivity. In the quest to deliver more signal, merely applying gain to amplify a weak signal is not the answer, since it also amplifies noise. To improve SNR, imagers must derive more signal from each photon while still controlling noise. Successive generations of devices have shown significant improvements in charge conversion efficiency (CCE) through better pixel designs and advances in wafer foundry processes, but sensitivity has not quite kept pace with speed increases. As a result, camera noise floors have steadily increased over the last decade, and SNR, especially in low light, has actually decreased (**figure 1**).

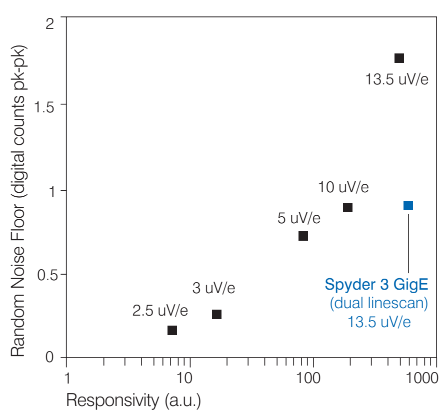

Figure 1: Random noise floor and CCE of successive camera generations.

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Lower noise. Noise is critical to any electronic system, and imagers are subject to a variety of noise sources. Amplifier noise, as already mentioned, requires sensor designers to expend significant effort in optimization. Reset noise is caused by the act of resetting capacitors on the sensor to a known level before they are used for the next exposures. Reset noise can be removed by correlated double sampling, either on-chip or off-chip. Sensors will also exhibit fixed pattern noise from various sources. Fortunately, regardless of source, if noise has a fixed pattern, it can be deterministically removed by subtraction (or addition).

But there is no quick fix for photon shot noise, a statistical phenomenon following a Poisson distribution resulting from the random variation in the number of discrete electrons captured when photons strike the photosensor. Photon shot noise is particularly problematic in high-speed low-light imaging, since it depends not on the signal voltage generated by the photons, but on the number of photons themselves. Arising from the quantum nature of light, photon shot noise cannot be separated from the signal itself. It is present before any signal processing or output operations, even before the act of detection. Increasing CCE to generate more voltage from each electron will not improve the signal to shot noise ratio.

Furthermore, photon shot noise has a sub-linear relationship with detected photons—it scales with the square root of the number of photons detected (**figure 2**). Doubling the number of photons only increases the shot noise by $\sqrt{2}$, and while this is good for bright light, it is bad for low light, since reducing photons by 50% (1/2) only reduces shot noise by ~30% ($1-1/\sqrt{2}$). As the available light decreases, photon shot noise becomes a progressively more dominant noise source. Despite advances in controlling any other noise sources, eventually shot noise will limit sensor and camera noise floors.

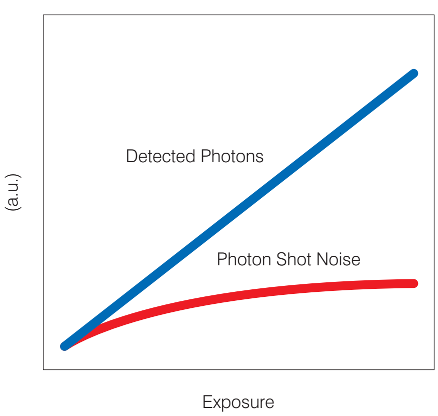

Figure 2: Detected photons and photon shot noise: sub-linear relationship.

Dodging shot noise with dual linescan

If photon shot noise limits performance, then the goal of designers will be to increase the number of photons collected. But with constraints on the size of pixels, the light intensity, and the exposure period, there are few options left for gathering more photons. Increasing quantum efficiency (QE) to capture as many available photons as possible is an obvious option, but boosting QE through processes like backside thinning is tricky and expensive.

A dual linescan CCD offers another path to collecting more photons, without requiring any semiconductor process development. Simply put, the design takes two exposures and combines them, doubling sensitivity with only a $\sqrt{2}$ increase in shot noise and thereby delivering a greater signal to noise ratio.

Functionally similar to TDI (time delay and integration) arrays, the design consists of two parallel arrays of photodiode pixels. Having twice the pixel area allows it to capture twice the number of photons compared to a single line with the same QE and CCE.

Each pixel is connected to a selectable delay gate that either allows charges through or delays the charges by one scan line (**figure 3**). As in all linescan devices, the line rate of the sensor must be matched to the motion of the object being imaged. 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. It then stores the collected charge in a delay line before combining it with the charge collected from the bottom array. Thus, the sensor can effectively combine two exposures.

Signal electrons from the two arrays (one delayed, one not) are combined on-chip into a single output. Since the charge is combined before the output amplifier, there is no increase in amplifier noise.

Like conventional linescan but unlike TDI, dual linescan allows exposure control. And its photodiode design is free of extra silicon gates that can interfere with blue response.

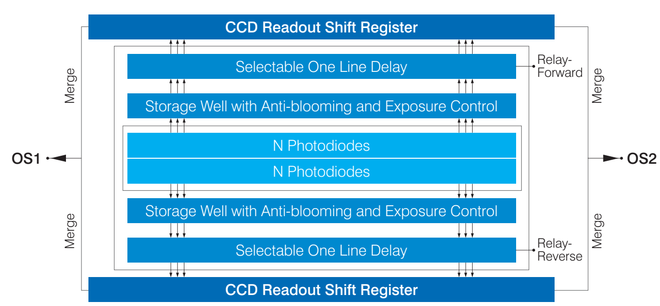

Figure 3: Structure of dual line scan sensor

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The main disadvantage of this design is an increase in dark signal from the doubled pixel area. But as mentioned earlier, most linescan applications call for high speed and very short exposures. In situations like these, the integration time is so short that the dark signal is negligible.

At first glance, it appears that the CCD capacitance (and hence the power dissipation) is twice that of a conventional linescan. However, each of the two CCD readout registers only needs to handle half the amount of signal charge, so the CCD capacitance is less than double that of a conventional linescan.

Proof of the design's high-speed low-light effectiveness can be found in Spyder 3 GigE linescan camera. In addition to the patented dual linescan architecture, the camera benefits from improved CCE so that it delivers three times the responsivity of its predecessor. It also delivers twice its predecessor's line rates (**figure 4)**.

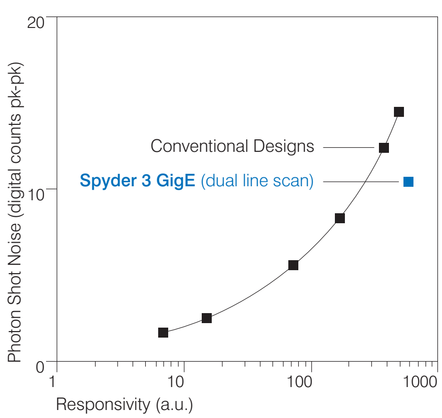

Figure 4: Photon shot noise as a function of responsivity

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