BASLER
VISION TECHNOLOGIES

CMOS High-speed Line Scan Cameras

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Over the last decade, customer demand for faster acquisition speeds in digital vision products has grown continuously, and there is no end in sight. A key component for meeting this demand in digital cameras is the ability to deliver growing data rates. This holds true for area scan cameras as well as line scan cameras.

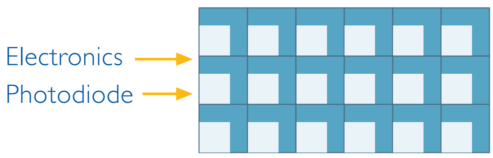
Up to now, most line scan cameras have been equipped with charged coupled device (CCD) image sensors. CCD sensors produce excellent image quality in slower applications, but they do face physical limitations when operating at higher speeds. In high-speed applications, the driving circuits for the sensors must work at high frequency against the high capacitive load of the CCD shift registers. This consumes a great deal of power and results in heating of the sensor and the camera electronics. For high speed, CCD sensors also need a multiplicity of output taps with off-chip output amplifiers and analog-to-digital converters (ADCs) on each tap. This tends to make CCD camera designs large and expensive.

To overcome these limitations, a new conceptual approach had to be found for line scan image sensors. For area scan cameras, complementary metal oxide semiconductor (CMOS) area scan image sensors have emerged and been established as a solution. CMOS sensors were invented in 1967, and CCDs made their appearance in 1969. Both devices are now roughly forty years old. Until in the 1990s, CMOS technology suffered from low lithography resolution. Also, CMOS fabrication processes optimized for image sensors were not available. But with the advent of CMOS active pixel sensor (CMOS-APS) technology, the sensors were virtually reinvented. Since they were introduced a decade ago, CMOS-APS sensors, especially those with column parallel ADC architecture, have rapidly become the first choice for high-speed area scan imaging. CMOS sensors not only exhibit superior performance in speed, but may also have a lower price.

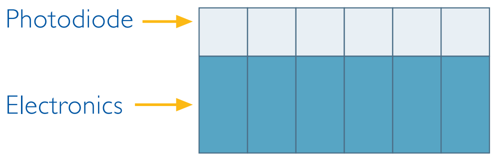
Due to improvements in chip fabrication technology, recently developed CMOS sensors show excellent noise and homogeneity characteristics. Solutions learned from CCD technology have been transferred in a step-by-step manner into the specialized CMOS image sensor (CIS) fabrication processes. As a result, today's CMOS sensors combine the advantages of both technologies: the superior imaging quality of CCD technology and the broad variety of CMOS circuit features.

With CMOS technology, it is possible to combine the sensor's photodiodes with other on-chip CMOS circuits. This is a big advantage compared to CCDs where almost all electronics must be off-chip and added at a board level. The on-chip circuit capability makes amplifiers, correlated double sampling (CDS) circuits, mixed-signal circuits such as multiplexers, or digital circuits such as timing generators available to CMOS image sensor chip designers. As demonstrated by the cell phone industry, the integration of additional intelligence into the image sensor can lead to dramatic decreases in price.

CMOS Area Scan Sensor



CMOS Line Scan Sensor

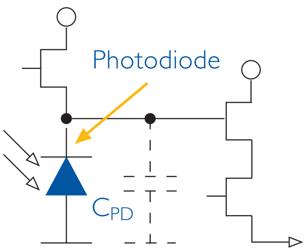


Comparing line scan CMOS imaging sensors to area scan CMOS imaging sensors reveals some important differences. In area scan sensors, because the pixel electronics must fit next to each photodiode in the pixel grid, the area for photodiode and electronics is limited. In line scan sensors, the photodiode can fill the entire nominal pixel area and the pixel electronics can be placed outside. The consequences are:

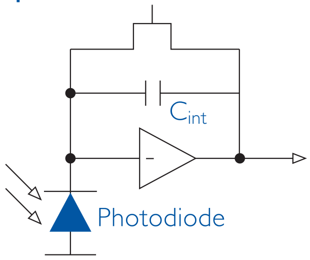
- The fill factor for area scan CMOS sensors normally ranges between 10% and 70%, whereas the line scan CMOS fill factor is actually 100%.
- Space requirements usually limit the transistor count on CMOS area scan sensors to 1.5 to 7 transistors per pixel, whereas there is no pixel level transistor limit for line scan CMOS.

This second consequence in particular presents a wide solution space for line scan CMOS pixel electronics. It also implies a large conceptual difference between line scan CMOS readout circuitry versus the typical area scan CMOS readout electronics and allows more advanced approaches.

Typical CMOS Area Scan Pixel



sprint Line Scan Pixel

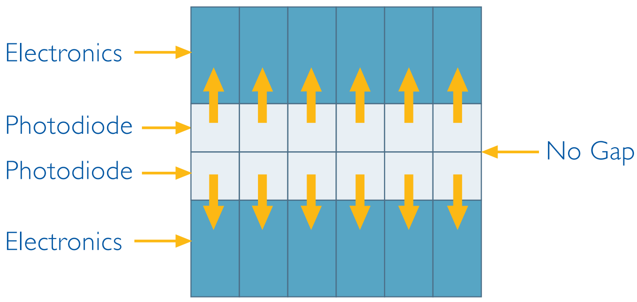


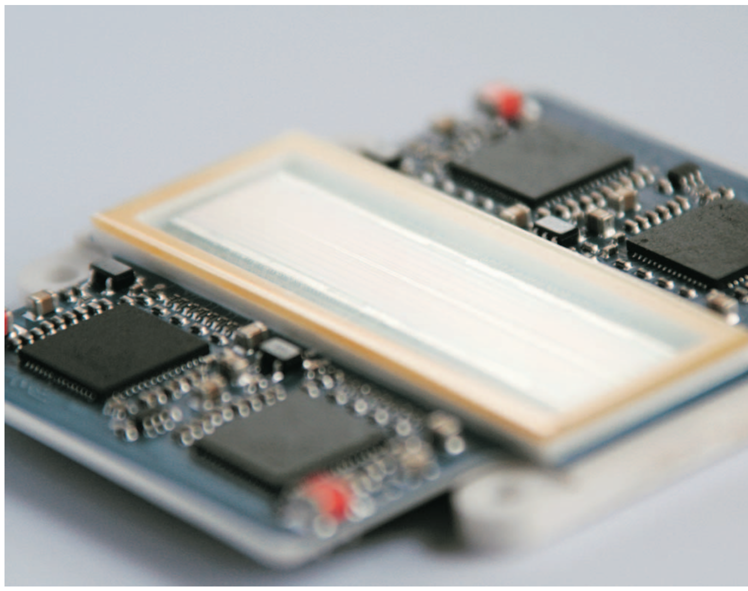
Consider analog gain, for example. Incoming photons are converted to photoelectrons that are translated into an analog voltage (U), usually expressed in µV, by a conversion capacity (C). To obtain a high gain, i.e., a high U, C must be small. In area scan, C is given by the photodiode junction capacity (CPD). And CPD needs a certain minimum size, i.e. a certain minimum capacitance, to be able to collect photons over the entire pixel. In line scan, the integration can be performed on a second integration capacitor (Cint), the value of which is completely decoupled from the pixel properties. This yields a high analog gain, which is an important prerequisite for good sensitivity.

Next consider noise. An important part of the sensor read noise is the so-called 1/f noise. The largest part of 1/f noise can be eliminated by performing correlated double sampling (CDS). In common CMOS area scan sensors, CDS is not performed because the required circuitry exceeds the amount of electronics that can typically be placed inside of a pixel. For CMOS line scan sensors, this area restriction does not exist, allowing for a true CDS circuit for each single pixel. Hence the temporal noise figures achieved with CMOS line scan sensors are superior in principle to the CMOS area scan temporal noise figures and compete quite well with the CCD temporal noise values.

The sprint family of line scan cameras from Basler Vision Technologies in Ahrensburg, Germany features the latest CMOS line scan image sensor technology and embodies most of the benefits mentioned above. In addition, sprint cameras offer a dual line of photodiodes. Each line has a 100% fill factor and the lines are situated with no intermediate gap between them. The camera can run at line rate up to 70 kHz in single line operation and 140 kHz in dual line operation.

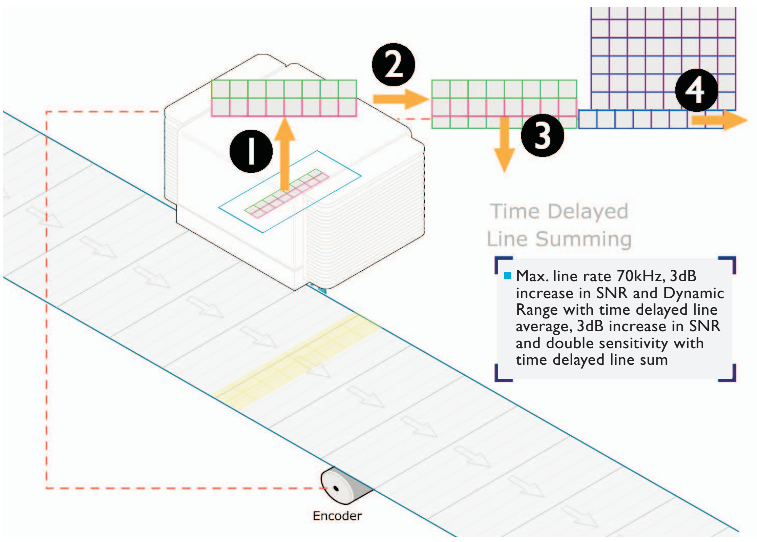
sprint Dual Line Scan Sensor





One of the benefits of a dual line sensor is that it can be used to double scan the object being imaged. This process is referred to as time delayed line summing or time delayed line averaging. With this feature, each area on a passing object is scanned twice; first by line A in the sensor and on the next integration, by line B. The image captured by line A is stored inside the camera and then combined with the image captured by line B on the next integration. Triggering is performed as normal. "Combining" can mean either the averaging or the addition of the gray values for the two captured lines. The time delayed line averaging technique has the advantage of reducing read noise and increasing the camera's virtual full well capacity, dynamic range, and signal-to-noise ratio (SNR) by nearly 3 dB each. This happens because the signal level remains constant while the noise is reduced by the square root of two (almost exactly 3 dB).

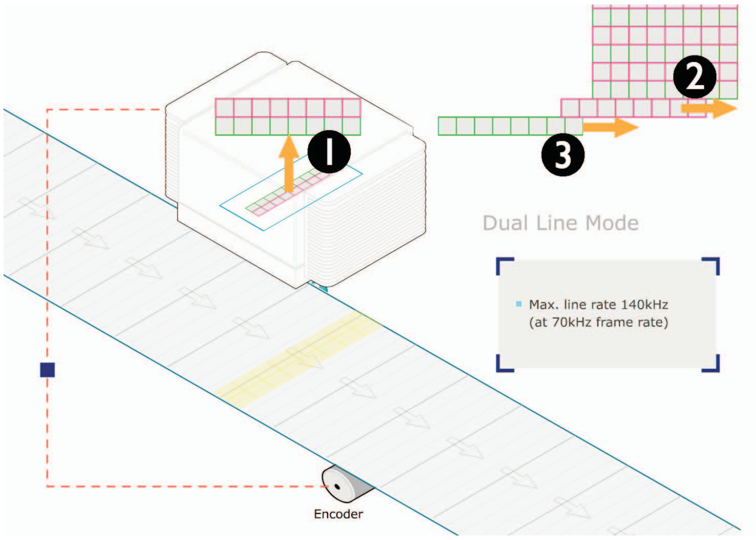
The time delayed line summing technique improves the SNR and the sensitivity by nearly 3 dB. In this case, the signal doubles and the noise increases only by the square root of two, which again provides a 3 dB SNR increase. The line rate for the averaging and summing techniques remains at 70 kHz as in single line operation.



*In **Time Delayed Line Summing Mode**, the camera is triggered at up to 70 kHz. Because the object moves by one line each time the camera captures two lines, each object line is scanned twice.*

- ❶ & ❷ *Two object lines are captured simultaneously on every trigger pulse.*
- ❸ *The first captured line (red) is summed with the second line (green) captured during the previous integration. They both represent the same image information.*
- ❹ *The sum forms the resulting image line (blue) with improved sensitivity and signal-to-noise ratio.*

The dual line sensor architecture can also be used to double the output line rate. In dual line mode, external triggering is maintained as usual. On every second trigger, a two line "frame" is captured (a frame being defined as the two lines captured by an exposure of the dual line sensor). Although the frame rate is only 70 kHz, because each frame contains two lines, the effective line rate is 140 kHz. A 140 kHz triggering rate will result in the camera outputting one line per trigger, as you would expect. Trigger preprocessing performed by the camera ensures that the image quality is exactly the same as you would expect from a single line camera operating at 140 kHz. The dual line mode does require proper triggering, with each trigger corresponding temporally to exactly one image line.



*In **Dual Line Mode**, the camera is triggered at up to 140 kHz, creating an output of up to 140 kHz. One line is transmitted per trigger, exactly as usual.*

- ❶ *The camera gets its first trigger pulse. The rate of the trigger pulses can range up to 140 kHz.*
- ❷ *The first captured line (red) is transmitted. The second captured line (green) is held in the camera.*
- ❸ *When the camera gets a second trigger pulse, the second captured line (green) is transmitted.*

On the third trigger pulse, two more object lines are captured. Because the conveyor belt has now moved ahead by two object lines, each object line is captured only once.

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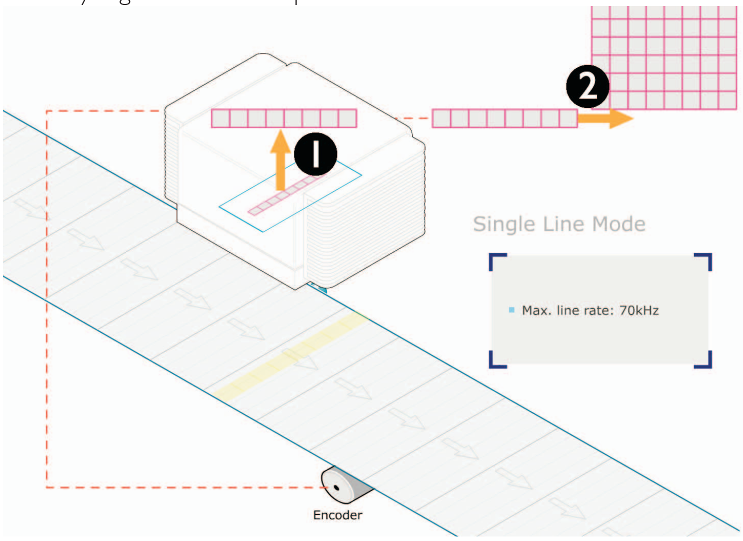
Some applications may require stepping back to the simple single line mode of operation. In this mode, only one line in the sensor is operative and the other line is switched off. The camera then works as if it were a true single line camera with a still very high line rate of up to 70 kHz.



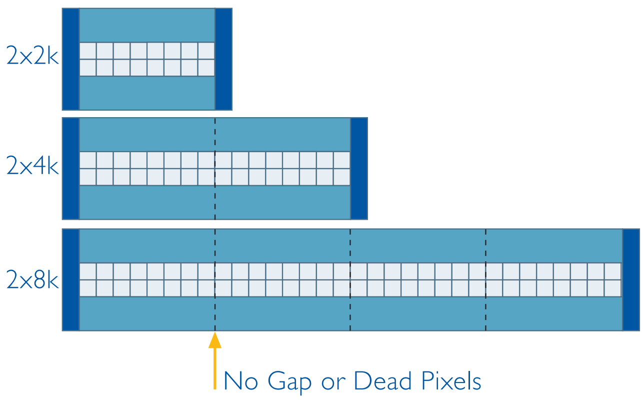
Single Line Mode:

1. *On each trigger pulse, the camera captures one object line.*
2. *The line is transmitted to the frame grabber where a two dimensional image is formed from the lines received.*

This is the conventional method for operating line scan cameras. The Basler sprint camera offers this possibility.

Sprint cameras are or will be available with 2 lines x 2k pixels, 2 lines x 4k pixels, and 2 lines x 8k pixels. To create sensors with 4k and 8k pixels, 2k sensors are stitched together at a wafer level. The stitching is done with a spatial tolerance of zero, and no dead or missing pixels are created at the 2 x 2k segment borders.

Sensor Stitching



The large amount of data generated by a sprint camera is transmitted to a host PC via the very common Camera Link™ interface.

Measurements indicate that sprint cameras have an equal or superior temporal noise level compared to state-of-the-art CCD cameras. Spatial performance and linearity also compare well with CCDs.

The sprint camera family is tailored for high line rates. A high line rate corresponds to a short integration time yielding a lower exposure and under the usual line scan lighting conditions, fewer detected photons. A high gain and excellent sensitivity are necessary to achieve good image quality at low exposure. With the sprint's full well capacity, good dynamic range can be achieved because the read noise is so very low.

In the long term, a technology shift from CCD to CMOS is expected in the line scan camera market, as has already taken place in the area scan arena. CMOS line scan technology is expected to spread rapidly and soon play a major role in the machine vision marketplace, especially in the high-performance range, i.e., high line rates and ultra-low noise.

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