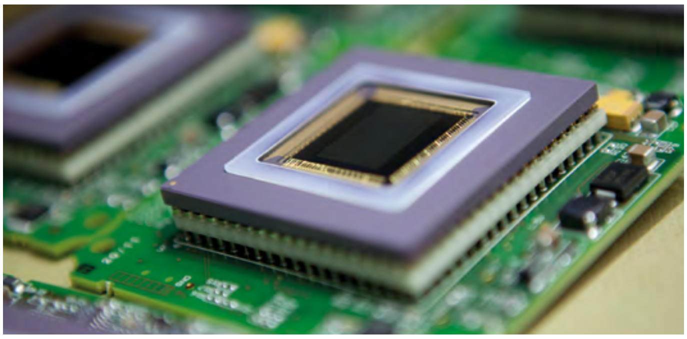
Modern CMOS Cameras as Replacements for CCD Cameras

In the beginning of 2015, Sony, the world's largest manufacturer of CCD sensors, announced to discontinue all sensors based on this technology. Many users are now asking what the latest CMOS sensors have as advantages over the old sensors, in particular, if they have been using CCD based cameras up to now. We would like to discuss this question more closely in this white paper in that we will briefly explain the sensor technologies, will compare the new CMOS sensors to the existing CCD sensors, and will provide tips as to when it makes sense to select a new camera with CMOS sensors. We will also explain what should be observed after integration.



CMOS Sensor

Content

1. What is the Difference Between the Two Sensor Technologies?

CCD (charge coupled device) and CMOS (complementary metal oxides semiconductor) image sensors are currently on the market. Their task is to transform light (photons) into electrical signals (electrons). This information is, however, transmitted by both sensor types using different ways and means and the design of each is also fundamentally different.

1.1 CCD Sensor Design

In CCD sensors the charges of the light sensitive pixels are shifted and converted into signals. The charges of the pixels, which are created by exposure to a semiconductor, are transported to a central A/D converter with the support of many very small shifting operations (vertical and horizontal shift registers), similar to that of a "bucket chain". The transfer of the charges is forced with the support of electrical fields, which are created by electrodes in the sensors:

1.2 CMOS Sensor Design

In the CMOS sensors, a capacitor as a charge storage is put in parallel to each individual pixel. This capacitor is charged with the exposure of each pixel by its photoelectric current. The voltage created in the capacitor is proportional to the brightness and the exposure time. Differently than CCDs, the electrons captured in the capacitors by the exposure of the sensor to light are not shifted to a single output amplifier but are transformed into a measurable voltage directly at the source by means of each pixel's own associated electronic circuit. This voltage can then be made available to the analog signal processor.

By using additional electronic circuits per pixel, each pixel can be addressed, without the charge having to be shifted as with CCDs. This results in the image information being able to be read much more quickly than with CCD sensors and that artifacts due to overex-

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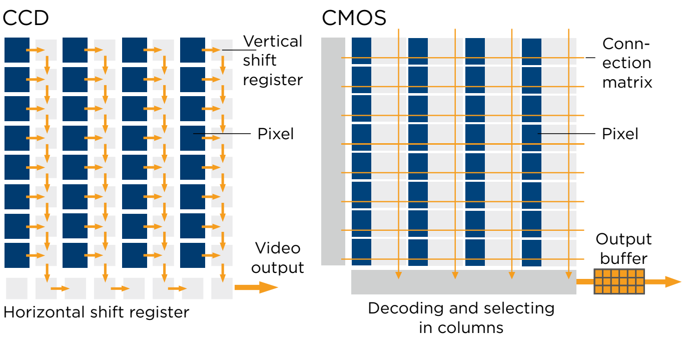
posure such as, for example, blooming and smearing, occur far less frequently or not at all. The disadvantage is that the additional space required for each pixels electronic circuit is not provided as a light sensitive area. The portion of the light sensitive area on the sensor surface (defined by the fill factor) is then smaller than that of the CCD sensor. Theoretically, for this reason, fewer photons for the image information can be collected. There are methods, however, for lessening this disadvantage.

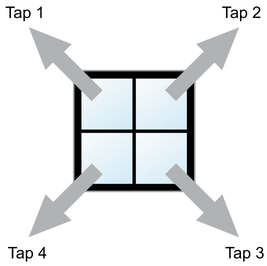


Design of a CCD sensor (left) and a CMOS sensor (right). The charge is shifted further pixel by pixel in the CCD sensor. In the CMOS sensor, on the other hand, the charge of each pixel is directly converted to a voltage and read, which makes the CMOS sensor noticeably faster.

2. When High Resolution is Required: The Multi-Tap CCD Sensor

The transfer of the charge in the CCD sensor requires a great deal of time. This is particularly a disadvantage with high resolution sensors in which the charging must be fed into the central amplifier by many shifting operations based on the large number of pixels. This narrowly limits the maximum frame rate. The technical response to this problem is the multi-tap sensor.

In the multi-tap sensor, the sensor surface is divided into multiple tap areas. Each tap area has its own electronic circuit, named the tap, for creating a signal and an individual output for each of the tap areas. The image information from the tap areas is shifted, amplified, and selected by the taps simultaneously over shorter distances and is therefore faster. These areas must later be reassembled into an image. The multi-tap process provides high resolution and speed but also has the disadvantage that it is very complex. The individual tap electronic circuits must carefully be adjusted on top of one another. Even the smallest deviations result in visible differences in the image, which are above all visible to the human eye because of the distinct boundaries of the tap areas. The energy consumption of multi-tap sensors is generally greater, which leads to increased heat generation. This has a tendency to increase the noise of the sensors and especially, as appropriate, to make cooling measures necessary.



4 Tap Sensor

Due to its internal design, high speed and high resolution can be realized with CMOS sensors without the necessity for using multi-tap architecture.

3. Reasons Why the Latest CMOS Sensors are Superior to the CCD Sensors

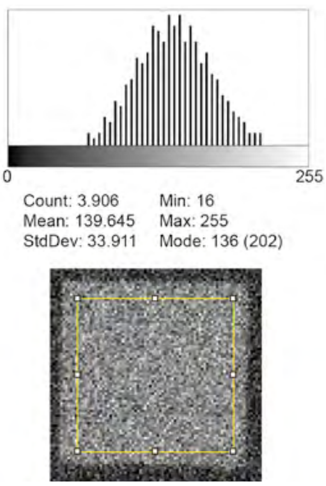
	CCD Sensors	New CMOS Sensors
Shutter	Global	Global or rolling
Costs for camera/ sensor for the same resolution	Very high	Middle (global shutter) to very low (rolling shutter)
Maximum read out speed	Oft nicht mehr als 20 fps	Very high, virtually unlimited (e.g. 4 MP global shutter sensors with 180 fps)
Electrical consumption	High	Low
Lens selection	Limited, because the sensor formats are mostly > 2/3"	Very large (1/4" – 1")
Heat generation and tends to be noisy if it has not been cooled[1]	Very high	Low
Image quality[1]: Dynamic range	Good	Low to very good
Image quality: Sensitivity[1]	Good	Low to very good
Image quality: Low noise[1]	Little	Little
Image interference by tap configuration[1]	May occur, must be laboriously calibrated (Only valid for multi-tap CCD sensors.)	No
Image artefact „blooming“	Yes	No
Image artefact „smearing“	Yes	No

[1] Comment regarding the table: The quality of the image depends greatly on the exact sensor type and the implementation of the sensor by the camera manufacturer.

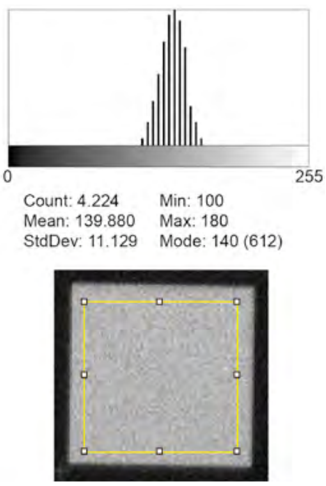
Only very recently have high resolution global shutter CMOS sensors been available. Many sensors were previously based only on the rolling shutter. The image quality of many CMOS sensors today is also superior to the image quality of CCD sensors. This is also one of the reasons why even the world market leader of CCD sensors (Sony) has discontinued CCD sensors and concentrates entirely on CMOS in the future.

An example from Intelligent Traffic Systems (ITS): the image on the left was taken with a 4 tap CCD sensor, the KAI4050 Sensor from ON Semiconductor (formerly Kodak). The image on the right was taken with the new CMOS sensor IMX174 from Sony. In the image on the right, a clearly higher dynamic range can be seen very well as it allows for the driver as well as the license plate to be better recognizable in the same picture. Additionally, with nearly the same settings, the sensor is clearly more sensitive and there are correspondingly more details in the background.

Sony ICX625[2]



e2V EV76C560[1]



[2] *Based on Basler piA2400-17gm, pixel size 3.5 µm*

[1] *Based on Basler acA1300-60gm, pixel size 4.54 µm*

A good comparison of image quality is the tendency for increased noise of a sensor with otherwise the same settings. The signal to noise ratio (SNR) is best determined by use of the image gray level spectrum (image above) of a homogeneous light gray surface (image below). The lower the width of the sprectrum of the gray values, the better. In the example the images of the light gray surface and their gray level spectra are shown: on the left for the CCD Global Shutter Sensor from Sony ICX625 and on the right for the CMOS Global Shutter Sensor EV76C560 from e2V. The influence of the pixel size has been eliminated.

4. When Should One Consider Changing Camera Technology?

If one or more of the following questions can be answered with „yes", then it is time to change to CMOS technology. This applies equally to existing systems as well as for new systems to be developed:

- Would I like to achieve an increase in the performance in my system by higher frame rates?
- Would I like to achieve an increase in the performance to also be able to see more under difficult light conditions?
- Does the heat generation in the camera present a problem? Does it have to be excessively cooled?
- Are image artefacts such as visible lines, blooming, or smearing a problem?
- Would I like to reduce costs as a goal of my system?
- Is the existing sensor technology discontinued or about to be discontinued?

5. What Should be Considered with the Latest CMOS Based Cameras with Regard to Integration?

If the decision has been made to change the sensor technology, a couple of things should be kept in mind to ensure a quick and effective integration: An advantage: The complete and highly complex sensor integration, including the optimization of the image quality is a part of the core know-how of the manufacturer and already established by the time you have the CMOS camera in your hands. In selecting a camera, the user only has to be concerned with the “exterior” points.

These include:

5.1 Determining the right camera for the necessary resolution, sensor and pixel size

In practice, resolution describes a measurement of how large the smallest possible distance between two lines or points may be so that they can still be perceived as separate from one another within the image. So what is specifically meant when you read a data sheet of a camera and it states: "2048 × 1088"? This information refers to the number of image points (pixels) per line, in this case 2048 pixels for the horizontal lines and 1088 pixels in the vertical lines of the image. Multiplied with one another the result is a resolution of 2 228 224 pixels, or 2.2 mega pixels (million pixels, MP).

A simple formula is used to determine which resolution is required for your application:

$$\text{Resolution} = \frac{\text{Object size}}{\text{Size of the detail to be inspected}}$$

The required resolution depends on which details you want recognized in the image.

Sensor and pixel size
Large surfaces, both on the sensor and also in the individual pixels themselves, offer more space to capture light. Light is the signal from which the sensor generates and processes the image information. The more surface area available, the better the signal to noise ratio (SNR), in particular for large pixels with e.g. 3.5 µm. The better the SNR, the higher the image quality. A good value is within the range of 42 dB.

Another benefit of a large sensor is the larger space on which more pixels can fit, which produces a higher resolution. The actual advantage here is that the individual pixels are still always large enough to guarantee a good SNR – as opposed to smaller sensors on which less surface is available for less large pixels.

Keep in mind that large sensors and many large pixels without the corresponding lens is only half the story. They can only achieve their full potential when combined with a suitable lens, also capable of depicting such high levels of resolution. Large sensors are also always more cost intensive, since more space always means more silicon.

5.2 Definition of the required camera interfaces
This decision depends, among other things, on the required cable lengths, bandwidth, the speed and real-time requirements and the availability of the PC hardware.

Here it is important that many CMOS sensors provide a high data rate and thus require a large bandwidth. As much as possible, for this reason also, a camera interface should be selected that supports a high bandwidth and nonetheless has a cost-effective infrastructure (e.g. GigE or USB 3.0). Then the system is well set up for the future if higher frame rates should once again increase the performance.

In the following you will find a concise graphic overview of the current camera interfaces and their advantages and disadvantages.

For further information about the camera interfaces, read our white paper, "Comparison of the Most Common Digital Interface Technologies (Camera Link®, USB3 Vision, GigE Vision, FireWire)."

Interface	Cable length	Band width maximum in MB/s.	Multi-camera	Cable costs	„Real-time"	„Plug & Play"
USB 2.0	5m	40	🟧	🟧	🟥	🟩
FireWire	4.5m	64	🟧	🟧	🟩	🟩
GiGE VISION	100 m	100	🟩	🟩	🟧	🟧
USB3 VISION	8 m	350	🟧	🟧	🟩	🟩
CAMERA Link	10 m	850	🟥	🟥	🟩	🟥

The various interfaces in overview

GigE Vision and USB 3.0 will dominate the interface market for some time and thus also for a swivel to CMOS is the best choice.

5.3 Selection of lens and lighting
If one decides on a new sensor format then a new lens should come with it as well. The lighting must also perhaps be adapted if the new sensor has a different sensitivity. In many cases even nowadays it is possible to increase performance and also reduce costs. So smaller pixel sizes also allow smaller lens formats, that are thus available more favorably priced (as long as the "optical" solution also fits). An example is the 1/2" lenses that provide more than 5 MP resolution.

5.4 Integration expenses for software and camera control
Cameras that conform to a current standard such as, for example, "GenICam[2]" or interface standards such as USB3 Vision or GigE Vision, are generally easy to integrate. Previous programming can possibly be maintained and only the necessary recording parameters are adapted. If the previous solution did not correspond to a standard, the integration is bound to be somewhat costlier, but it can still be worthwhile to do it: The new solution should be prepared enough for the future so that also other, less expensive cameras can also be integrated at any time.

[2] *Generic possible options for the digital camera*

5.5 Selection of the next suitable camera

With this check list, you can determine the right CMOS camera. In doing so you should keep in mind the following points with respect to your old CCD solution:

- **Optical format and pixel size**
  It should stay the same if no change in the lens is desired. It can be smaller if the sensitivity is greater and a lens change is possible.

- **Frame rate**
  Ideally it should be higher (to achieve performance improvements in the system)

- **EMVA data**
  Should be the same or better[3]

- **Sensitivity / wave length**
  It should be similar if the lighting cannot be adapted.

- **Design size of the camera**
  Should be the same or smaller

- **In camera firmware functions**
  These should be compared in detail if particular firmware functions have been used up to now. Modern CMOS based cameras usually offer more functions: Examples include sharpening or noise reduction algorithms

- **Software and programming**
  If the processing had previously been done with software that conformed to standards (e.g. GenICam and GigE Vision), then keep in mind that the same compatibility should be used so that as little adaptation as possible needs to be made to the programming. If proprietary software was used, more time should be allowed for making adaptations to the programming. Changing to software that conforms to standards is therefore recommended.

- **Camera interface**
  The same interface, if USB 3.0 or GigE; for older interfaces or grabber based interfaces, making a change should be considered to reduce system costs and/or to have a more sustainable design for the future.

Tools can help to answer all of these questions in finding the optimal CMOS camera to succeed a CCD camera. Basler thus offers a camera selector, for example, on its web site, that significantly simplifies the selection of a CMOS camera, based on criteria such as optical format or frame rates.

6. Summary

Modern CMOS sensors are generally superior to multi-tap CCD or standard CCD sensors. And that not only is with regard to the price, but also because of unambiguous technical advantages, such as higher speeds, higher resolutions, fewer picture interferences or negligible heat generation. The integration of new CMOS based cameras as an exchange or alternative to CCD sensors can also be a simple process, especially if the user selects hardware and software that conforms to standards. For your application, this means that, for example, the throughput for inspected parts may clearly increase, and that for clearly lesser costs for camera and inspection systems and without having to simultaneously make cuts in the image quality.

[3] EMVA data represent a good opportunity to compare the essential imaging characteristics of a sensor and/or a camera

Autor

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About Basler

Basler is a leading manufacturer of high-quality digital cameras for applications in factory automation, medicine, and traffic monitoring. Product development is led by the demands of industry. The cameras offer simple integration, compact sizes, excellent image quality, and an outstanding price/performance ratio. Basler has more than 25 years of experience in image processing. The company employs nearly 500 colleagues at its headquarters in Ahrensburg and at locations in the USA, Singapore, Taiwan, China, Japan, and Korea.