CMOS cameras rise to speed challenge

Cameras based on CMOS image sensors are providing a new cost-effective way to perform high-speed imaging. **Gerhard Holst** describes the latest technology on offer.

Advances in CMOS image-sensor technology are making it possible for a new breed of high-speed cameras to capture events previously impossible to image by conventional CCD cameras. Improvements in chip design and manufacturing have enabled CMOS cameras to become a cost-effective, high-performance solution for imaging a wide range of transient phenomena, ranging from car crash-tests and ballistics, to muscle contractions and animal movements. Nevertheless, for extremely fast imaging at frame rates of more than a few thousand frames per second (fps), specialized mechanical or image-intensified cameras that use CCD sensors are still required.

CMOS and CCD characteristics

There are several inherent advantages CMOS sensors offer over traditional CCD sensors in high-speed imaging. Firstly, high-speed imaging requires high frame-rates. This necessitates short exposure times and strong illumination, which can cause blooming (regions of overexposure) and smear (unwanted stripes) in CCD sensor images. In contrast, the high-speed response and wide dynamic range of CMOS sensors means that bloom and smear are not usually a problem.

Prior to recent improvements in semiconductor manufacturing, CMOS sensors were limited by a sensitivity far inferior to CCDs. But now, higher pixel fill-factors, combined with the use of light-gathering microlenses, make it possible to achieve similar sensitivities. What's more, the higher dark-current (noise) of CMOS sensors is not an issue in high-speed applications, because the exposure times are so short.

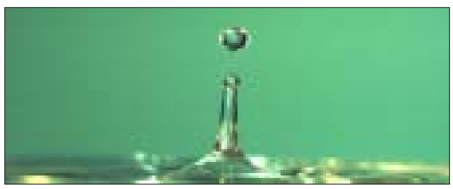
The most important advantage of CMOS image sensors is, without doubt, their highly parallel architecture. This enables a very fast read-out that can reach several thousand frames per second (see the table below). It is impossible for CCD image sensors to reach the high read-out rates of CMOS cameras because the pixel data is output through a serial scheme.

Further advantages of CMOS cameras are that they use single-voltage supplies and have low power-consumption, which is important for high data-rates. The only disadvantage is the higher fixed-pattern noise of CMOS sensors caused by small differences in pixel gain. However, this can be corrected later on, when the images are recorded.

Performance today

Due to the absence of mass-market applications, there is a lack of high-speed CMOS image sensor chips on the market. As a ▷

PCO and S Weiss



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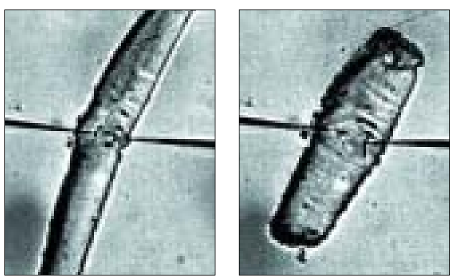

O Friedrich, Institut für Physiologie

Transient phenomena: a sample of the image sequence of a chocolate biscuit falling into a dish of milk (top), a water droplet into water (middle) and the contraction of a muscle cell (bottom).

Typical performance of a high-speed CMOS camera

	HG-100K	phantom v9.0	ultima APX-RS	visario g2	pco.1200 hs
manufacturer	Redlake	Vision Research	Photron	Weinberger	PCO
resolution [pixel × pixel]	1504 × 1128	1600 × 1200	1024 × 1024	1536 × 1024	1200 × 1024
frame rate, full frame [fps]	1000	1000	3000	1000*	636
dynamic A–D [bit]	8	10	10	10	10
camRAM, maximum [GB]	4	12.26	16	4	4
minimum exposure [μs]	5	1	2	10	0.05

*The camera uses a specific read-out scheme to achieve the frame rate: only half the number of pixels is read out and, by sophisticated algorithms, the image is reconstructed.

result, most high-speed camera manufacturers specify and order their own proprietary CMOS sensors. However, off-the-shelf CMOS image sensors are available from from Micron (Photobit) and Cypress (FillFactory).

In terms of performance, the table on p43 gives an overview of the typical camera specifications available today. The maximum frame-rate is around 1000 fps at a full-frame pixel resolution of 1600 × 1200, with 10-bit analogue-to-digital (A-D) conversion. Unfortunately, in many cases, no information is given about the dynamic range of the cameras, but this is often likely to be in the region of 59 dB.

All the manufacturers listed in the table offer monochrome and colour versions of their cameras. As today's camera interfaces cannot cope with high frame-rates, all the cameras have built-in camRAM (primary-configured image memory), which can be expanded according to customer needs.

Although the shortest exposure times are in the microsecond and nanosecond regimes, the achievable value is often limited by the quality of the illumination of the object.

As for pixel read-out speeds, multiplying the frame rate by the image resolution gives speeds of the order of 3–4 Gpixel/s. Noise levels are typically 25–35 electrons, with the exact level determined by the inherent transitor noise (kTC noise) of the pixels' photodiodes (light-sensitive elements of a pixel). The achievable dynamic range is around 60 dB or more, depending on the depth of the A-D conversion.

Purchasing advice

As is common when purchasing scientific equipment, it is the application that determines which parameters to consider when buying a high-speed camera. The primary factors are sensitivity, resolution, frame rate, noise, shutter speed and price. Depending on the application area, other important parameters might include the following:

- visible image quality (signal-to-noise ratio, dynamic range, colour conversion), especially in the case of TV and broadcasting;
- high geometrical accuracy for 3D-tracking applications;
- synchronization of multiple-camera and trigger options for crash-tests and ballistics;
- size of the camera's camRAM;
- the features of software supplied, for example, the availability of application program interfaces (APIs) for common software packages, and software-development kits.

A related issue is the amount of image data generated during an imaging task – 4 GB of camRAM can easily be filled up with a couple of seconds of imaging. With this in mind, it is vital to have a fast interface, such as Camera-Link, to transfer the data to the PC for processing. Interfaces based on the new PCI XPress bus could improve this situation in the future.

Weinberger

Crash-test image taken with a Weinberger visario g2.

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Super-slow-motion recording of single water drops.

Last, but not least, a critical and often overlooked factor is illumination of the target. This issue should not be underestimated, because, as frame rate increases, exposure times per frame get shorter. Short exposure times require powerful arc-lamp lighting, which is driven by AC voltage and thus repeatedly turned on and off. This can cause flicker in imaging at high frame rates. It is advisable that, in addition to spending time selecting the right camera system for an application, the user also thinks about the most appropriate illumination system (DC-driven LEDs might be one solution).

Emerging applications

What are the most popular applications for sophisticated CMOS camera systems? Historically, aside from scientific research, the automotive industry has used high-speed cameras to analyse the deformation of cars as they crash. As a result, it has been a strong driver in improving high-speed imaging.

In crash tests, G-stable camera systems are mounted inside the car and external cameras also record the crash sequence. In order to get exact measurements, the precision of the triggering of the cameras is crucial.

Another increasingly important application area is the life sciences, where high-speed cameras can help to analyse fast biological events, such as muscle contractions. In this field, sensitivity is an important factor, as many applications require imaging via a microscope.

In TV and broadcasting, high-speed systems are often used for super-slow-motion sequences in sports, movies or adverts. Many readers will be familiar with advertising video sequences showing beverages being poured into glasses in slow motion.

In industry, high-speed systems can help to perform materials testing – imaging the moment when a piece starts to break, or investigating malfunctions in production machines that cannot be seen with the naked eye. Fluid and gas flow can also be visualized by high-frame-rate imaging techniques such as particle image velocimetry (PIV). PIV systems are used to study many phenomena, including the injection processes in engines, water-wave development in geochemical research, and aerodynamics in wind tunnels.

CMOS cameras are so versatile that only very high-speed applications are outside their reach. Applications such as spark analysis, ballistics of space debris and magnetic field effects may require 10 000 fps, which, today, can only be achieved using special mechanical solutions that deliver exposure times in the range of 3–5 ns.

However, continual improvements in semiconductor and computer technology mean that the performance of CMOS cameras is likely to get faster in the future. This will open the door to the high-quality, cost-effective visualization of even more events. □

Gerhard Holst is head of the science and research department at PCO AG, a provider of high-performance CMOS and CCD cameras based in Kelheim, Germany. See www.pco.de.

Acknowledgements

Joost Seijnaeve, FillFactory (Cypress) and Christian Backert, Weinberger GmbH.