SCIENTIFIC HIGH-SPEED CAMERAS: APPLICATIONS & TECHNIQUES

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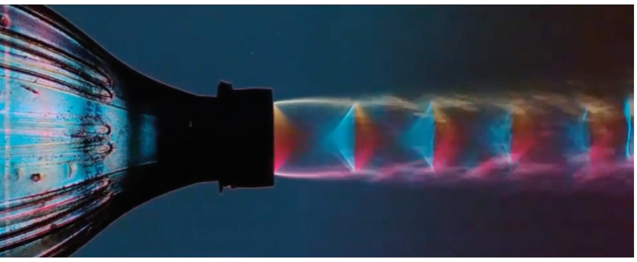

This article discusses the progression of high-speed cameras, along with some of the key working principles, key definitions, the means by which high-speed CMOS sensors are characterized, and the wide diversity of applications and techniques high-speed cameras are used within.

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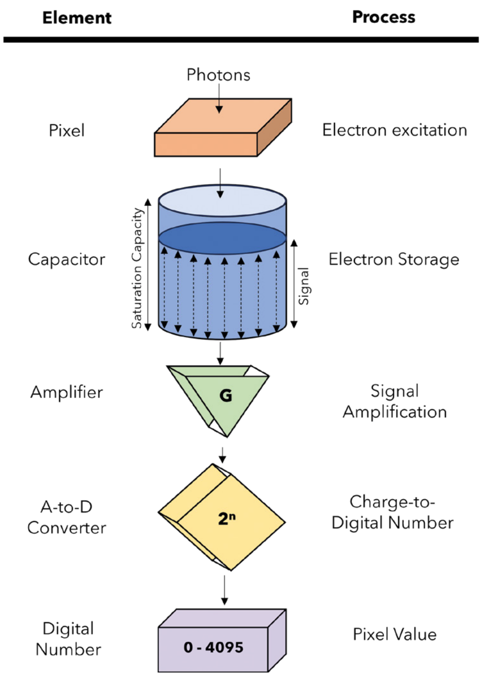
High-speed cameras have become a cornerstone of modern research and development, serving as key scientific components that have been enabling scientists, engineers, and technicians to both visualize and measure high-speed phenomena. Much like how a microscope provides the ability to finely divide space for human visual inspection, a high-speed camera acts as a "time microscope" allowing researchers to leaf through ultrashort slices of time that occur on timescales otherwise imperceptible to the human eye & mind. In this article, we will discuss the current state of commercial high-speed scientific cameras, together with the basic working principles & emerging features, and then highlight some of the new and exciting high-speed applications.

Figure 1: Schematic illustration of the conversion of incident photons to a resulting pixel value.



PRINCIPLE OF OPERATION

There are a range of different types of high-speed cameras, with the most common type (and the focus of this article) utilizing complementary metal-oxide semiconductor (CMOS) sensors. CMOS sensors consist of an array of photodiodes that convert incident photons into electrical charges, with each photodiode unit corresponding to a 'pixel' in a resulting image. When photons are absorbed by the pixel, a proportional charge is generated and then highly parallelized A/D converters subsequently convert the charges to digital data, as either 8, 10 or 12-bits (typical for high-speed cameras), an abbreviated workflow is shown in Figure 1. To capture color images, a Bayer filter array is placed over the sensor, allowing pixels to capture only either red, green, or blue light; and the color information is reconstructed through interpolation. Once digitized, the image data is rapidly written to onboard RAM that exists as a circular memory buffer under the first-in, first-out (FIFO) method. This technique permits users to record up to tens of gigabytes per recording (generally seconds of record time), with available image systems trending toward terabyte-sized onboard RAM.

TECHNOLOGICAL PROGRESSION OF SENSOR THROUGHPUT

One of the most critical performance metrics in the high-speed camera market is sensor throughput, which is the product of the max sensor resolution and the max frame rate (at the resolution), expressed in gigapixels per second (Gpix·s^{-1}). To date, high-speed sensor offerings generally range from either 1, 4, or up to 9 Mpix. Over the past decade and a half there has been rapid progress, as shown in Figure 2, where clear improvements in throughput have been made for both 1 and 4 Mpix cameras systems. To give a clearer picture, the 40- and 75- Gpix·s^{-1} systems can achieve frames rates of ~10 kHz at 4 Mpix and ~76 kHz at 1 Mpix, respectively. High-speed sensors can also generally be 'windowed' to achieve faster frame rates. A 75 Gpix·s^{-1} system can achieve frame rates of ~1.75 MHz at 41 Kpix (i.e., 1280 × 32).

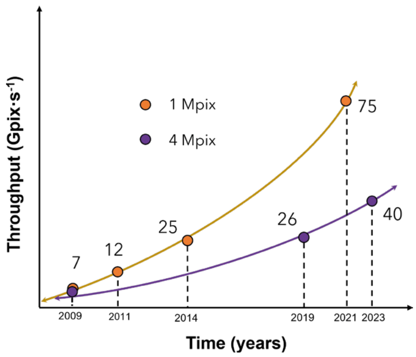
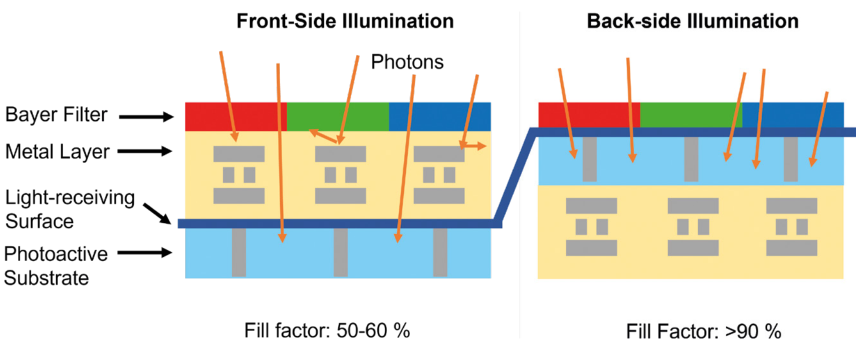


Figure 2: This graph compares the sensor throughput, measured in Gigapixels per second (Gpix·s^{-1}), of two high-speed sensor platforms: one with a 1 Mpix resolution and the other with a 4 Mpix resolution since 2009.

BSI TECHNOLOGY & SENSITIVITY

The high-speed camera industry, in part, has recently transitioned to Backside Illuminated (BSI) sensor technology, over the traditionally implemented Front-side illuminated (FSI), see Figure 3 for comparison. In short, BSI sensors are designed with the photoactive layer un-occluded by the metal layer, enabling more efficient light collection. Going to BSI was recognized as a requisite for the continued development of camera systems with exceedingly fast framing rates (and low integration periods) due to the fact that as the integration gets shorter there is a direct linear reduction in light-gathering ability (i.e., less signal, lower SNR). Thus, the large improvement in Fill Factor, going from 50-60% to now upwards of >90% with BSI was critically important. Note: Pixel response to incident light is directly proportional to pixel area × quantum efficiency × fill factor. The improvement ●●●

Figure 3: Comparison of FSI (Front-Side Illuminated) vs BSI (Back-Side Illuminated) Sensor Architectures. In the FSI architecture (left), photons (represented by orange arrows) must pass through the metal wiring and other layers before reaching the photodiode, which leads to light loss due to obstruction and reflection. In contrast, the BSI architecture (right) allows photons to enter directly into the photoactive region of the pixel, improving light capture efficiency.



in pixel responsivity has allowed the incorporation of ultrashort exposure times, now down to 38 ns.

SCIENTIFIC APPROACH TO SENSOR PERFORMANCE

Some camera manufacturers use the EMVA 1288 standard to characterize image sensors. This is a scientific approach and currently is the best means for guiding camera users to an optimal image sensor for a given imaging application. Some of the key terms derived from EMVA testing are in Table 1.

SNR VS SIGNAL PLOT

The Signal-to-Noise Ratio (SNR) versus signal plot, as defined by the EMVA 1288 procedure, is a crucial evaluation method for assessing the performance of image sensors. According to the EMVA 1288 standard, this plot is constructed by measuring the SNR at various signal levels, typically obtained from a series of test images captured at different light intensities (irradiances). The irradiation level is plotted on the x-axis, while the SNR is plotted on the y-axis. The SNR is calculated by the ratio of the signal amplitude (usually the mean pixel value) to the respective noise at that signal level. This plot reveals several critical values, namely the absolute sensitivity threshold or AST. This demarks precisely how many photons (at 50 µs integration) are required to produce an SNR = 1, Figure 4, blue arrow. This is the key specification for low-light applications, like in fluorescence, bioluminescence, screen imaging, or applications demanding ultra-short exposure times. This plot also provides an SNR across the ‘mid-gray’ region of the sensor, and thus users can discern precisely how sensitive the sensors are to change at any light-level, Figure 4, green arrow. Lastly, this plot also provides how many photons are required to bring the pixel to saturation, which is critical information for those who are characterizing scenes with wide

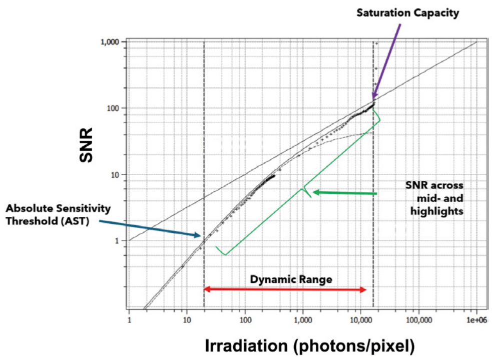


Figure 4: The EMVA 1288 plot illustrates the relationship between the Signal-to-Noise Ratio (SNR) and incident irradiation on a sensor. The curve demonstrates four key performance characteristics: AST (absolute sensitivity threshold), Dynamic Range of the sensor, SNR at all irradiation levels, and the Saturation Capacity.

Table 1: Scientific Sensor Specifications (EMVA 1288)

TERM	UNIT	DESCRIPTION
Quantum efficiency (QE×FF)	%	Percent of photons incident on a pixel that get converted to electrons at the specified wavelength (λ). EMVA bundles QE and fill factor (FF) value together, and a singular QE x FF-value is generally reported, where λ ~ 532 nm. This term has a direct linear correlation to sensor responsivity.
Temporal dark noise (TDN)	e-	Noise present in an image when there is no incident light on the sensor (i.e., lens cap on). This value is signal-independent, and represents the lowest noise value on a sensor, and is also traditionally known as ‘Read Noise’. This term is paramount for defining sensor effectiveness in low light applications.
Signal-to-noise ratio (SNR_{max})	ratio dB bits	Maximum signal-to-noise (SNR) ratio a pixel can produce. This value is extracted from the highest pixel response (i.e., right before saturation) since SNR trends with the square root of the signal. A higher value indicates better image quality and higher light-level-resolution in the mid-gray and bright parts of an image.
Absolute sensitivity threshold (AST)	p	Quantity of photons (p) required for a pixel to generate a signal that is equal to the noise (SNR = 1). This is measured for integration times of 50 µs and fixed wavelength (i.e., 532 nm). The lower the number, the more sensitive the sensor, and the better a given sensor will perform in low-light applications like fluorescence, bioluminescence, ill-lit scenes & ultra-short exposure times.
Saturation capacity	Ke- Kp	Amount of charge (Ke-) or photons (Kp) a pixel can take just before saturating. This is also known as Full Well Capacity (FWC). Since most sensors are Shot noise limited, the SNR_{max} generally directly correlates with square root of the saturation capacity.
Dynamic range	ratio dB bits	Ratio between the max pixel signal measurable to the lowest signal resolvable. Represented in ratio as saturation capacity (SC) : temporal dark noise (DN) OR SC:TDN; in units of dB as -20 log (SC/TDN), or in units of bits or ‘stops’ we have $n = \log_2(SC/TDN)$.

‘scene-dynamic-ranges’, see Figure 4, purple arrow. The higher the saturation capacity, and the lower the absolute sensitivity threshold, the larger the sensor dynamic range, Figure 4, red arrow.

TEMPORAL, SPATIAL, AND LIGHT-LEVEL RESOLUTION

The sensor specifications should always match or exceed the requirements of the imaging application. To ensure the sensor performance is at least minimally viable (in terms of temporal, spatial, and gray-scale resolution), it always helps to utilize the Nyquist rate ($f_{Nyquist}$) to define the minimum frame rate needed to prevent aliasing of the event rate (f_{event}), where:

$$f_{Nyquist} = 2 \times f_{event}$$

The Nyquist rate mandates that the event or entity being measured is sampled at 2× the rate of the event. For

APPLICATIONS	TECHNIQUES	POST PROCESSING
Ballistics and Range	Schlieren & Shadowgraph	Object Tracking
Materials Analysis	Microscopy Imaging	Digital Image Correlation
Microfluidics	Optical Tomography	Particle Image Velocimetry
Automotive and Rail	Polarization Imaging	Size & Shape Analysis
Combustion Imaging	Spectral Imaging	Vibrational Analysis
Life Sciences & Biomechanics	Image Intensification	High Dynamic Range
Welding Imaging	Laser Imaging	Image-to-Spectrum
In-line Inspection	Extending dynamic range	Background Oriented Schlieren
Commercials/Media	Tracking Mounted	Optical Tomography
Aerospace & Wind Tunnels	Scintillator Imaging	Upscaling & Denoising
Nuclear Reactions	Stereophotogrammetry	Edge Detection
Plasma Imaging	Data Synchronization	Kinematic Analysis

Table 2: Where and How High-speed cameras are Used

example, if an event occurs at 1 kHz, the minimum frame rate required is 2 kHz. To collect the highest quality recordings, generally users sample the event 10 - 20× the event frequency, thus frame rates of 10 - 20 kHz are often used to visualize smooth temporal transitions. The same approach is viable for spatial resolution, where if one is looking to characterize small subject matter (i.e., 10 µm features or particles), the magnification of the system must be high enough to provide at least 2 pixels to span the subject, hence a minimum image resolution would be 10 µm / 2 pixels, or 5 µm / pix. Like temporal resolution, having 10 - 20× higher produces cleaner data. Lastly, if the event of interest is expressed as very small fluctuations in irradiance, one needs to ensure that the noise level (at that signal level) is less than the incident signal-delta you aim to characterize. Thus, analyzing the SNR vs signal plot in the EMVA 1288 is essential.

SPECTRAL RESPONSIVITY

In addition to the key specifications laid out in the EMVA 1288 report, also of importance is the pixel behavior across the entire UV-visible-NIR spectrum. In general, the EMVA 1288 testing procedure is carried out at one specific wavelength (i.e., 532 nm with noted FWHM), while spectral responsivity plots provide the pixel response (Amps-per-Watt) versus wavelength. A sample spectral response curve is shown in Figure 5a for a red, blue, green, and monochrome pixels from 300 - 1100 nm.

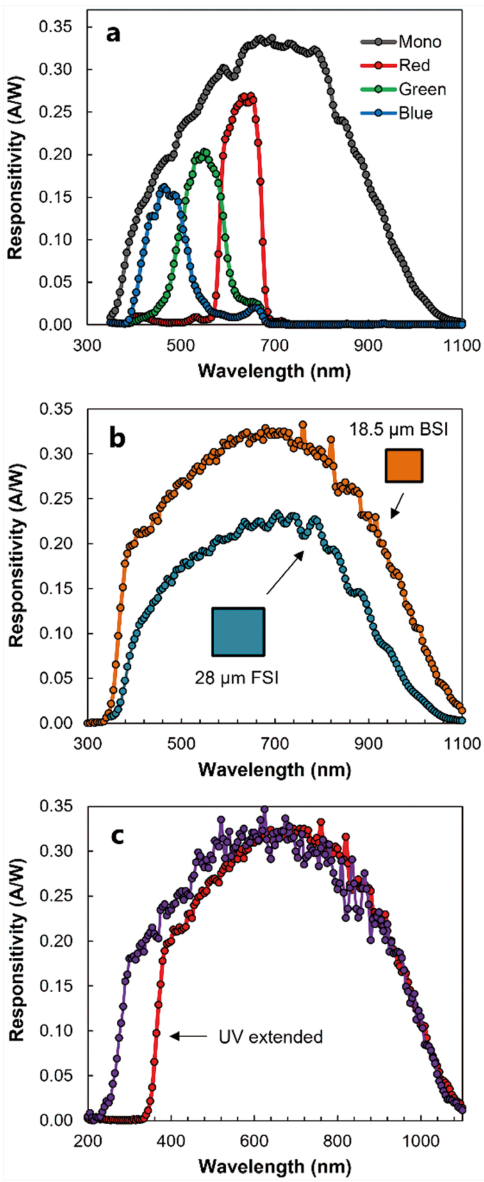


Figure 5: The spectral responsivity curves for: (a) typical sensor with red, green, blue, and monochrome pixels, (b) BSI vs FSI pixels, and (c) UV-Extended *vs.* non-UV-extended sensor spectral response.

RADIOMETRY

The sensor spectral response curves can be used to perform radiometric measurements for irradiance measurements, spectroscopic measurements, or optical pyrometry. If the incident spectrum I(λ) and S(λ) are known, the pixel response (PR) is simply:

$$PR = k \times \int_{\lambda min}^{\lambda max} I(\lambda) \cdot S(\lambda) d\lambda$$

For a simple monochromatic source incident on a sensor, one can approximate the pixel response, or back out the incident irradiance, Φ_λ by utilizing the following equation:

Pixel Response [e–] =

$$\Phi_\lambda \left[\frac{p}{\mu s \cdot \mu m^2}\right] \times PA\ (\mu m^2) \times QE_\lambda \left[\frac{e}{p}\right] \times FF \left[\frac{ActivePixelArea}{TotalPixelArea}\right] \times ET\ [\mu s]$$

FSI VS BSI

With the introduction of BSI to high-speed cameras, we now have a marked increase in fill factor and thus pixel response. Before this transition, it was common to estimate pixel relative responsivity purely by pixel size, however, this is not great practice any longer. The spectral responses of a 28 µm FSI pixel and an 18.5 µm BSI pixel are plotted in Figure 5b. Notice that despite the much smaller pixel, the BSI pixel will outperform the FSI pixel substantially. • • •

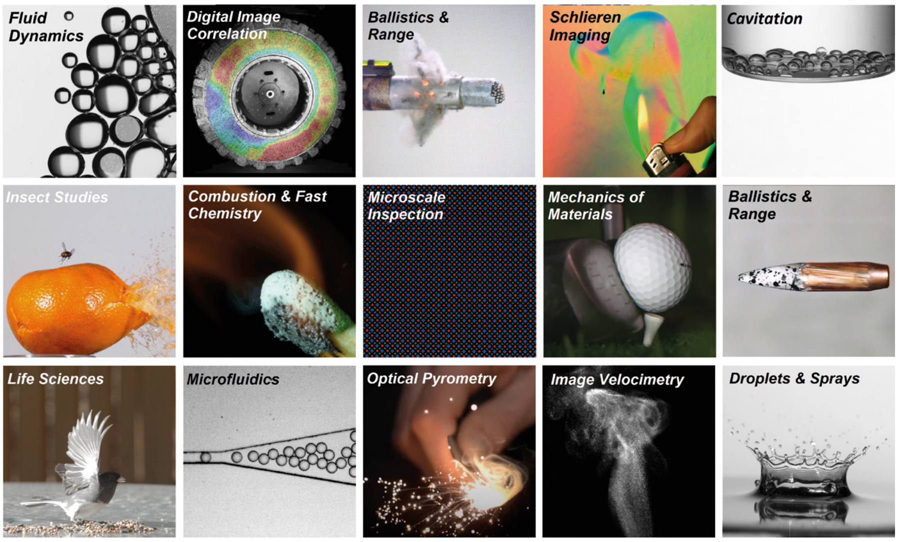
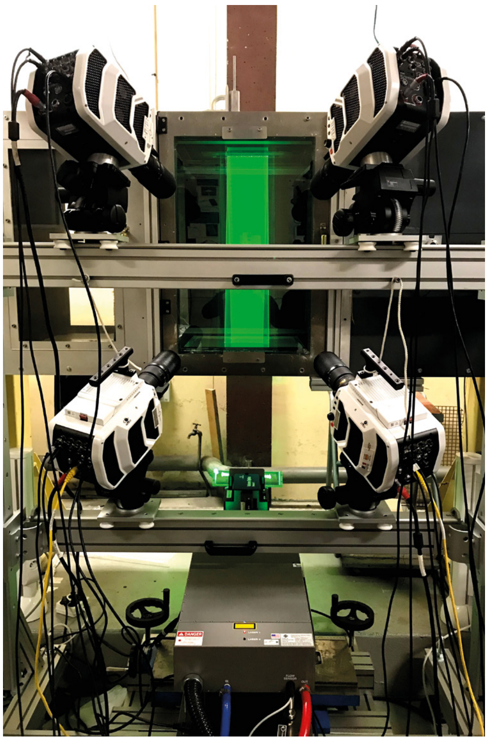


Figure 6: A series of still images extracted from high-speed videos to illustrate the wide range of applications high-speed cameras are involved in. Still-images generated from Phantom high-speed cameras, provided by Kyle D Gilroy & co (Vision Research, AMETEK).

Figure 7: A four-camera setup for performing volumetric PIV studies. TOMO-PTV-4D Study of Hybrid electroactive morphing European Projects, IMFT, LAPLACE & FERMAT federation. Using integrated actuator-sensor design to improve aircraft wings aerodynamic performances HORIZON-2023-2027-PATHFINDER-Open-Project N° 101129952-BEALIVE-"Bioinspired Electroactive multiscale Aeronautical Live skin".



UV EXTENSION

The transition to BSI has also resulted in improved sensitivity in the UV region, where sensors can achieve over 70% QE at 300 nm. This is due both to the avoidance of glass microlenses (which absorb UV) and with the addition of a UV-transparent cover glass on the sensor. Figure 5c illustrates the spectral difference between the same sensor, one with cover glass and the other with UV-transparent cover glass. This makes UV-BSI sensors highly effective for applications that require UV sensitivity down to 250 nm, such as UV/Vis spectroscopy, combustion research (OH* imaging), fluorescence imaging, and others.

A MEASUREMENT TOOL

High-speed cameras have evolved from simple imaging devices into sophisticated scientific instruments capable of performing precise measurements on recorded video, see Figure 7 for a high-speed imaging setup with four synchronized cameras performing volumetric PIV analysis (PIV – particle image velocimetry). Modern image sensors, which measure the amount of light hitting each pixel, allow high-speed cameras to function as powerful radiometric *and* photogrammetric tools. As such, high-speed cameras can be used to transduce (from images) displacement, speed, acceleration, strain, vibration, temperature, and also density & flow gradients with Schlieren optics.

APPLICATIONS & TECHNIQUES

High-speed cameras are currently being deployed in increasingly advanced imaging applications across academic, industrial, and government research laboratories. Listed below are some common and emerging applications and techniques of high-speed cameras. Figure 6 shows a small subset of examples of how high-speed cameras are being used.

CONCLUSION

High-speed cameras have become indispensable tools in research and development across academia, government, and industry, enabling groundbreaking advancements in fields such as materials science, biomechanics, aerospace, and automotive engineering. As high-speed camera technology continues to advance, we will be sure to witness improved frame rates at higher sensor resolutions, together with improved sensor performance to ensure the highest possible data quality.

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IX	https://ix-cameras.com	IX cameras
IDT	https://idtcameras.com	Integrate design tools