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For machine-vision systems, smaller is not always better when it comes to pixels.

When digital cameras need large pixel areas

Keith Wetzel and David Frosini

The emergence of the digital still camera (DSC) into the consumer market has produced a new generation of megapixel charge-coupled devices (CCDs). But even with more than a million pixels, these devices have small physical pixel areas that work well for consumer photography but have drawbacks for more-demanding industrial, commercial, scientific, and medical applications. Here, larger pixel areas are better. This is one of the few cases where smaller is not necessarily better.

A typical 1/2-in. optical-format megapixel DSC-CCD, for example, features approximately 1400 × 1000 active elements with square pixels 4.65 µm on a side. The same-resolution CCD in a 2/3-in. format has pixels that are 6.4 µm on a side. For a 1-in. format, the pixel size increases to 9.3 µm (see Fig. 1 and table; see also "Full-frame vs. interline CCD architecture," p. S16). While all of these CCDs have the same pixel count, they perform quite differently because the physical size of each pixel is a key determinant of system performance.

Digital-still-camera CCDs use small pixels to minimize their overall size, and the cost impact is dramatic. The trade-off is fine for many consumer photography applications, but not for applications such as machine vision, security, and inspection. In these cases, it is critical for users to understand how CCD pixel size affects the responsivity, dynamic range, frame rate, and even the cost of the optical system. For example, the performance trade-offs are generally not acceptable when pixel size drops below 6 µm.

The impact of pixel size

The quantum efficiencies (photon-to-electron conversion ratio) of most CCDs are similar, but the size of the photosensitive area makes their performance unequal. Responsivity is a measure of the signal that each pixel can produce and is directly proportional to pixel area. As the responsivity increases, the same amount of signal can be collected in a shorter period of time or, conversely, more signal can be realized during a fixed exposure time. For systems limited by photon shot noise, this means the signal-to-noise (S/N) ratio is higher (see Fig. 2).

Another benefit of increased responsivity is that less illumination is needed to achieve a desired S/N level. Or, with low-level illumination, the image will have a higher S/N ratio and appear less grainy. The system frame rate can also be increased, providing increased throughput.

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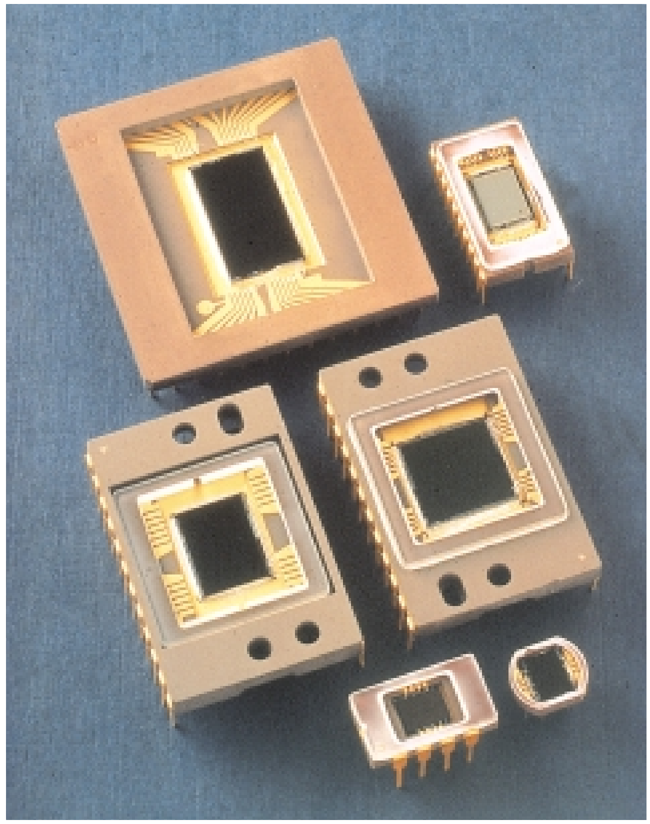

FIGURE 1. Historically, the optical format value for a CCD derives from the days when Vidicon vacuum tubes were used as sensing elements in television cameras. A 1-in. vidicon tube approximately 1 in. in diameter has a photosensitive area with a diagonal of 16 mm (about 2/3 in.). A CCD with a 16-mm diagonal is thus called a 1-in. CCD. Eastman Kodak makes interline CCD sensors in a variety of sizes.

Pixel area also affects the dynamic range of the camera system. Each pixel is like a well that stores up charge during its exposure period before it is read out. The larger the pixel area, the larger the charge capacity, and the higher the signal level. A pixel is saturated when further increases in illumination do not create a corresponding increase in signal voltage. Larger pixel areas help improve dynamic range because they hold more charge, so brighter objects do not saturate the pixel. In fact, the technical definition of dynamic range is the ratio of the saturation voltage to the total noise of the DSC. Because camera system noise is generally independent of pixel area, increasing the pixel size gives a higher S/N ratio.

Wide dynamic range allows areas of high brightness and low brightness to be seen clearly and simultaneously. The camera system can thus easily distinguish objects in shadows or a dim object positioned near a bright object, such as a resis-

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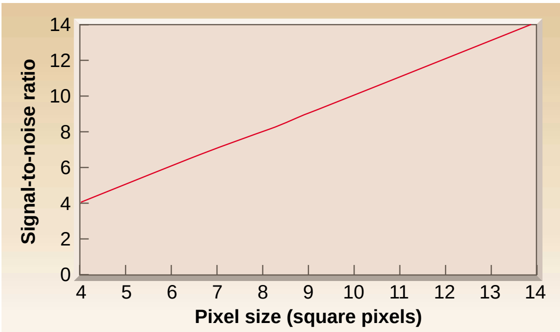

FIGURE 2. Increasing pixel size increases signal-to-noise ratio for digital still cameras limited by photon shot noise at constant lamp intensity and exposure time.

tor next to a reflective metallic trace on a printed-circuit board. It also is easier to discern variations in dark or shadowed areas of an image, such as in digital x-ray images.

Dynamic range is sometimes characterized by the number of gray levels in a camera system—which is a measure of how much contrast an image can display. An 8-bit digital system can produce 256 gray levels, whereas a 10-bit system can provide 1024 gray levels. Machine-vision applications typically require a CCD dynamic range of 60 dB, which corresponds to a 10-bit CCD and 1024 gray levels.

Nevertheless, warns Gary Erickson, an industrial camera product manager at the Motion Analysis Systems Division of Eastman Kodak (San Diego, CA), users must be careful when looking at the gray-level specifications for a camera. “The analog-to-digital conversion electronics may be able to support 10 bits,” says Erickson, “but if the CCD produces only 8 bits of dynamic range, the extra 2 bits created by the analog-to-digital converter are useless. You won’t see 1024 different gray levels.”

Dynamic range also drops as the camera frame rate (and thus total noise level) increases. Buyers should consider the conditions under which noise and other parameters are measured by the camera vendor. Sometimes, specifications describe dynamic range performance at low frame rates, so when the camera is used at standard video frame rates (30 or 60 frames/s), dynamic range and performance will be lower than expected.

Exploring optical performance

Pixel size also affects the interaction of the camera lens with the microlens array on interline CCDs. The microlens on top of each pixel focuses light rays onto the photosensitive part of the pixel. The microlens significantly increases responsivity but it also limits the angular range of good responsivity. A 5-µm pixel typically has a severe drop in responsivity at 5° from normal incidence. This leads to an optical effect whereby pixels near the edge of the camera lens field of view collect light less efficiently than at the center. This effect is reduced with larger 9-µm pixels, which have high responsivity at angles out to 15° or more.

Shrinking the CCD sensor array also affects the imaging optics required in front of the CCD. In general, the optical system must have an aperture with a wider angle (a lower *f* number) to maintain the same field of view as with a larger-pixel design. Focal length must also be shorter, assuming the optics diameter remains constant. Toshi Hori, president of camera system manufacturer Pulnix (Sunnyvale, CA), says to expect some problems when the focal length of the optics becomes too short, less than about 10 mm.

“While a DSC-CCD is less expensive than a larger-pixel CCD, unless higher-quality optics are used, image quality will suffer,” Hori noted. “For example, there can be nonuniformities and vignetting, or a dark ring around the image.”

Evaluating a CCD camera system is a complex process. It requires precise knowledge of the conditions under which the application is carried out. A small-pixel-area CCD system may, for example, be adequate for determining the presence of a certain feature as long as there are no bright reflective areas, the lighting is sufficient, and the processing algorithms can function with only modest contrast levels. Many industrial applications, however, require the imaging capabilities possible only with large-pixel-area CCDs. ❏

Pixel sizes for a 1400 × 1000 square-pixel array

OPTICAL FORMAT	SENSOR DIAGONAL	PIXEL SIZE
1 in.	16 mm	9.3 µm
2/3 in.	11 mm	6.4 µm
fi in.	8 mm	4.65 µm
1/3 in.	6 mm	3.5 µm

Full-frame versus interline CCD architecture

The two basic types of CCD architecture are full-frame and interline. A camera with a full-frame sensor must control exposure with a mechanical shutter or strobe light. The entire surface of the CCD is used for light sensing, charge storage, and readout. With the shutter open or strobe light on, charge accumulates in all of the pixels.

For a given pixel size, a full-frame CCD generally will have higher charge capacity, lower dark signal, lower noise, and higher responsivity, particularly in the near-infrared, than an interline CCD. A strobe light used with a full-frame CCD provides bright illumination that is effective for very fast acquisition times. Mechanical shutters work well with long exposure times when light level is low.

Interline architectures are either interlaced or progressive scanning. With progressive scanning, the horizontal lines of the CCD are read out in order, from top to bottom. These CCDs are best for computer-based applications such as robotics. With interlaced scanning, first the odd and then the even rows are read out. These are best for video-based applications.

All interline CCD devices use an electronic shutter mechanism to control exposure time. They do not require special strobe lights—ordinary room lights or lamps can provide the illumination source. ❏