P1-12: Comparison of Modern CCD and CMOS Image Sensor Technologies and Systems for Low Resolution Imaging[1]

Bradley S. Carlson

Symbol Technologies, Inc.
Holtsville, NY, USA
bcarlson@symbol.com

Abstract

CMOS image sensors were introduced to the market in 1995 and in the past three years have taken significant market share from CCD sensors in the low-end digital camera markets (e.g., web cams). CMOS sensors boast low power dissipation, single supply operation and camera-on-a-chip integration, and CCD sensors boast high sensitivity and low noise. The sensors are based on inherently similar technologies (silicon photodetectors and CMOS read-out electronics); therefore one would expect they share the same fundamental limits. We analyze CMOS and CCD detector systems from the architecture down to the sensitivity of the pixel and read-out electronics. Our analysis shows that for low resolution imaging (VGA and below) CCD and CMOS sensor technologies are converging to practically indistinguishable solutions in terms of performance, size and cost.

Keywords

CMOS sensors, CCD sensors, detector sensitivity measurements.

INTRODUCTION

In this paper we compare CCD and CMOS image sensor solutions for low resolution cameras. Low resolution cameras are used for machine vision applications, consumer web cams and imaging mobile devices such as cellular phones and personal digital assistants [1,1,5]. We compare CCD and CMOS image sensors from the system architecture down to the experimental sensitivity of the sensor pixels. Many comparisons of the technologies have been published (e.g., [3]), but few have looked at commercially available technologies and compared them from a system point of view. As is shown in this paper even pixel sensitivity should be viewed from a system point of view.

The research efforts in CCD and CMOS imaging technologies over the past 40 years have had significantly different emphases. The focus for CCD sensor technology was on detector sensitivity and little attention was given to system integration, power dissipation and supply voltage requirements. The focus for CMOS sensor technology was exactly the opposite; the interest was in using off-the-shelf CMOS fabrication processes so little attention was given to detector sensitivity. In the past 5 years the research emphases for the two camps has changed and both have addressed their weaknesses. The result is two sensor technologies that are converging to indistinguishable solutions.

Also presented in this paper is a method for the experimental evaluation of image sensors. The method is used to measure the signal-to-noise ratio (SNR) of the system in a way that it can be related to pixel sensitivity. It is a relative measure, but suitable for comparing detectors with pixels of different sizes. The key to the method is establishing equivalent optical systems for each sensor and normalizing with respect to pixel size. The signal-to-noise ratio is computed from digital images, so it characterizes pixel sensitivity of the entire read-out chain from the detector through the analog read-out electronics and A/D converter. This method is necessary because most CMOS sensors include an integrated A/D converter making it difficult to take measurements on the analog video signal. Furthermore, it is desirable to measure pixel sensitivity this way because system performance is a function of the entire read-out chain.

We are interested in measuring random temporal noise only, since fixed pattern noise can be corrected with digital processing. To measure temporal noise the noise is computed on the difference between two identical images taken at different instances of time [4]. An advantage of this measurement technique is that it eliminates the need for an integrating sphere. We provide detailed measurements of pixel sensitivity for 6 CMOS sensors and 4 CCD sensors. We measure sensitivity to visible and near infrared light. The sensitivity of the CMOS sensors measured vary significantly, but it is clear the sensitivity has improved in recent years. This is primarily due to the customization of the CMOS fabrication process for image sensors. One CMOS sensor in our experimental set measures up to a typical CCD sensor in sensitivity and noise performance.

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We compare the architectures of modern CCD and CMOS camera solutions and specific implementations. This is where CCD technology has overcome its weaknesses in system integration and power dissipation. One CCD sensor in our experimental set has achieved the integration level and power dissipation of a typical CMOS sensor.

SENSITIVITY AND SNR MEASUREMENT

The traditional definition of sensitivity is signal per unit luminous flux-time, where signal can be volts or least significant bits and luminous flux is measured at the detector focal plane. This definition is satisfactory for sensor arrays where photon shot noise is the dominant noise source. However, it may not be satisfactory for low light conditions, especially in the case of CMOS sensors where there are additional noise sources at the pixel. In this paper we define sensitivity as SNR per unit luminous flux-time. Sensitivity, as we define it, cannot be characterized with a single number because the noise is dominated by different noise sources depending on the intensity of illumination. We characterize sensitivity with a curve of SNR as a function of luminous flux for a fixed time period of exposure.

To measure the sensitivity of an image sensor precisely it is necessary to focus onto a pixel a selected number of photons and measure the SNR at the output of the sensor. The number of photons focused on a pixel is a function of the target illumination and optics. Rather than counting photons we can measure the scene illumination of the experiment in lux or foot-candles using a light meter. When measuring the scene illumination in this manner one must be careful with the configuration of the digital camera system to be sure that measurements of cameras with two different sensor arrays are comparable. The main issue is pixel size and we address this issue below.

One can measure the sensitivity of a pixel of the detector, or the sensitivity of the camera system. To measure the sensitivity of the camera system, the SNR of the digital image can be measured. For most digital cameras, especially CMOS cameras, the selection of the analog signal processing and A/D conversion circuitry cannot be separated from the selection of the sensor. The ADC is either integrated with the sensor (as is the case for CMOS), or an integral part of a dedicated chip set (for CCD). Thus, the real concern is the performance from photons to bits and not just the performance of the pixel and read-out electronics.

A measurement of lux or foot-candles does not include a measure of the near infrared (NIR) radiation reflected from the target. The NIR introduces an error in the absolute SNR measurement; however, because all of the devices we are characterizing are silicon-based devices their responses in the NIR are similar[2]. It is also possible to use an IR filter with each camera to eliminate this source of measurement error. Our application does not require filtering, so we prefer not to use it in the measurement. For our experiments we use a halogen light source and neutral density filters to vary the scene illumination.

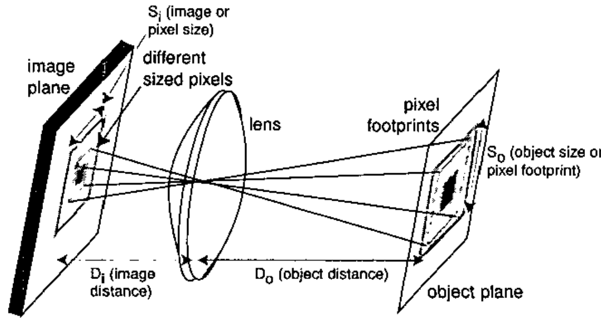

Figure 1. Digital camera pixel footprint in the object plane.

Optics

The amount of light collected by an optical system from a point source is proportional to the area of the aperture divided by the distance of the source squared. Given a system with circular aperture of radius r and a point source at distance D_o, the light collected by the optical system and focused onto a focal plane is

$$E_{fp} = E_{sc}\, r^2/D_o^2,$$

where E_{fp} and E_{sc} are the focal plane and scene illuminance, respectively. To compute the amount of light reflected from a target we integrate over the surface of the target (or source).

The optics of a camera forms an image of the target on the detector array. The optics can also be thought to image the detector array onto the target (Fig. 1). With this in mind each pixel is imaged to an area of the target in the object plane known as the pixel footprint. Thus, the amount of light received by a pixel is given by $E_{sc}r^2S_o^2/D_o^2$, where S_o is the size of the pixel footprint. To compare sensors with different pixel sizes one must choose a method where the same amount of light is focused on each pixel independent of pixel size. For different sensors the optical systems should be chosen such that the pixels of the different sensors have exactly the same footprint (S_o) in the object plane and the optical systems have the same diameter aperture (2r). Cameras with identical optics and different sized pixels have different sized pixel footprints. Suppose the target reflects a constant number of photons per unit area, then cameras with identical optics, identical integration times and different sized pixels collect a different

[2] CCD devices optimized for NIR sensitivity are excluded from our experiments.

number of photons per pixel. Cameras with different pixel sizes can be made to have the same pixel footprints by choosing appropriate lens designs. The lenses will have different magnifications (different focal lengths), but need to have the same diameter aperture (different F/#'s). This can be achieved using a zoom lens provided the lens has enough freedom in focal length to achieve the required field of view for any sensor one wishes to analyze. For our experiments a suitable zoom lens could not be found.

An alternative approach to using a zoom lens is to use exactly the same lens for each camera system and measure the pixel footprint in the object plane. Knowing the scene illumination and the pixel footprint in the object plane one can normalize relative to one sensor the amount of light (signal) focused on each pixel. In addition, this method corrects for variations in target distance from one experiment to the next. The pixel footprint can be measured easily by imaging a ruler or other calibrated dimensioning device.

Signal Measurement

The pixel signal is measured as the statistical mean of tens of thousands of measured responses of pixels from a single image. Hence, the measured responses of spatially distinct pixels are used as an approximation to measured responses of a single pixel at different points in time. The assumption here is that the responses of all of the pixels are similar and the illumination on the target is uniform. To correct for variations in signal offset from one sensor array to the next the signal is computed as the difference in response between a white and black target.

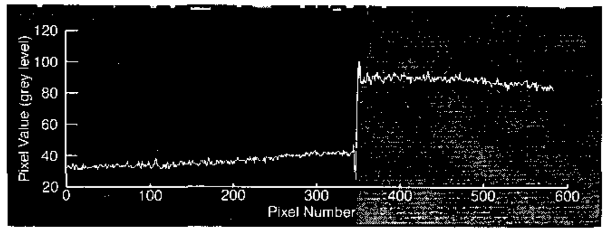

Figure 2. Sample image used for the signal-to-noise ratio measurement, and a line profile through the image.

Noise Measurement

Noise power is measured as the sum of the statistical variances of the measured responses to white and black targets. To compensate for nonuniformities in illumination and pixel response the variance is computed on the difference between two identical images taken at different times [4]. The noise measured is temporal noise only, and is a measure of total output-referred noise from all of the noise sources in the system.

The signal-to-noise ratio is computed as

$$SNR_{dB} = 10\log((\mu_w-\mu_b)^2/.5(\sigma_w^2+\sigma_b^2))\ dB,$$

where μ_w, μ_b, σ_w and σ_b are the means and standard deviations of the measured signals from the white and black targets. An example image showing the waveform of a line profile is given in Fig. 2.

Although the signal measurement is normalized with re-

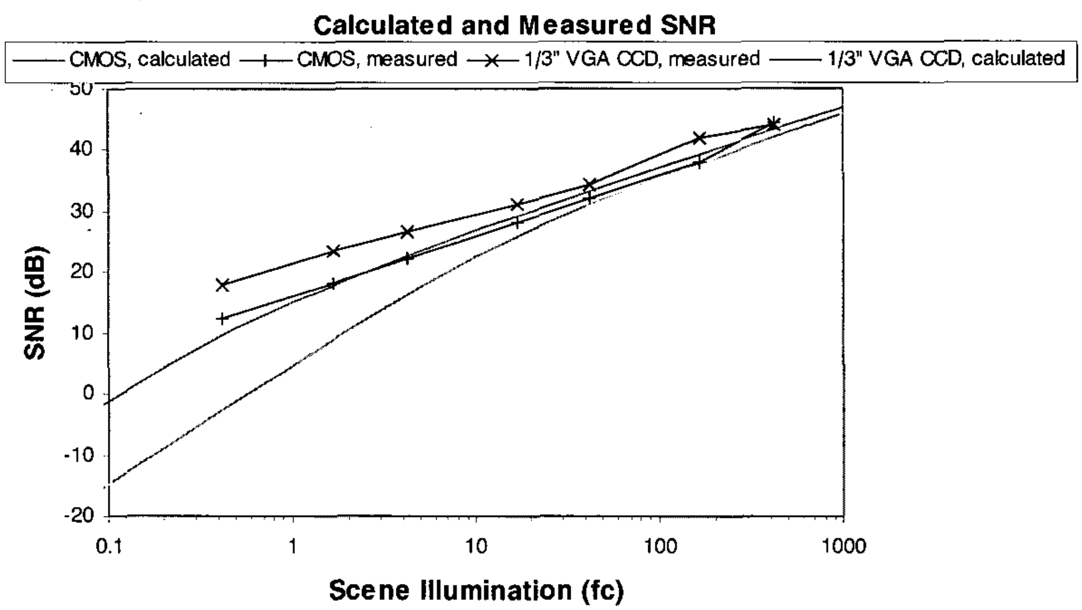

Figure 3. Comparison of measured and calculated SNR for two cameras.

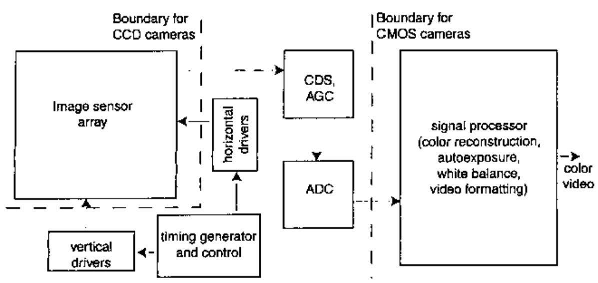

Figure 4. Block diagram of a typical digital camera system.

spect to pixel size the noise measurement is not. Noise sources such as shot noise are proportional to signal, but other noise sources such as thermal noise are not. Since noise sources are not separated in the measurement, it is difficult to normalize the noise with respect to pixel size. Furthermore, we are mostly interested in the performance in low light conditions where the noise is not dominated by shot noise. The SNR will be underestimated for sensors with large pixels at high illuminance levels, but will be accurate in low light. The measurement described here is sufficiently accurate for the comparison of sensor performance for most commercial or consumer applications.

ACCURACY OF THE MEASUREMENT METHOD

We compare the measured results using our method versus calculated SNR for one CCD camera and one CMOS camera. The results are given in Fig. 3. To simplify the calculation we assume illuminance of a single wavelength (550 nm). The measurements are very accurate for high illuminance levels, but are overestimated for low illuminance. An IR-cut filter was not used in the experiment, and the light meter used to measure scene illuminance does not measure IR. In addition, the neutral density filters do not extend into the IR. Thus, the error in low light is due to the IR photons imaged by the sensor. For high illuminance the IR is a small fraction of the total energy, so the error is minimum. Nevertheless, the relative comparisons of different sensors are valid.

CMOS VERSUS CCD SENSORS

Exponentially increasing efforts have been made during the 90's to commercialize CMOS image sensor technology. The effort has increased from a few companies in the early to mid-90's to 30 or more companies today. The advantages most often cited for CMOS imager technology over CCD technology are low power dissipation, single supply voltage, system-on-chip integration and low cost. However, in the last few years companies have advanced CCD technology in each of these areas and maintained the sensitivity and noise advantages of CCD imagers over CMOS imagers. CCD chip sets exist today that require a single supply voltage, are low cost and compete with CMOS in terms of integration and power dissipation.

Consider the block diagram of a miniature color camera system for portable or mobile devices (VGA resolution or smaller) as shown in Fig. 4. A typical CMOS camera is implemented with two chips where the boundary between the chips is after the A/D converter and before the signal processor. Today, a CCD camera can be built with two chips as well, but the boundary between the two systems is between the sensor output and the CDS input. The CCD camera still requires large positive and negative voltages, but they are generated internally from an external 3-volt supply with an integrated charge pump. The CCD system uses three integrated circuits, but two of the ICs are contained in one package using multichip packaging. For a color camera system the cost of the CMOS and CCD chip sets are similar, but for a monochrome camera the CMOS solution is less expensive because the signal processor IC is not required. In a CCD camera the signal processing IC is still required even if the color processing is not used. The only remaining distinguishing characteristic between CMOS and CCD sensors is sensitivity and pixel size.

The SNR measurement method described above has been used to characterize 4 CCD cameras and 6 CMOS cameras. The CCD cameras are all based on commercially available CCD sensors. All of the CMOS cameras are based on commercially available CMOS sensors with integrated ADC. Their characteristics are summarized in Table 1. These are cameras that were available from 1998 through 2001. All of the cameras have a linear response to light except for CMOS 2, which has logarithmic response.

Table 1. Descriptions of sensors tested.

Sensor	Pixel size (μm)	Transfer Method	Generation
CMOS 1	10	APS[3]	Pre-1999
CMOS 2	12.5	Continuous time	Pre-1999
CMOS 3	8.4	APS	Pre-1999
CMOS 4	7.5	APS	Pre-1999
CMOS 5	7.5	APS	Post-2000
CMOS 6	7.5	APS	Post-2000
CCD 1	7.5	Interline	N/A
CCD 2	5	Frame	N/A
CCD 3	5.6	Interline	N/A
CCD 4	4.5	Frame	N/A

The results of our measurements for all of the cameras are summarized in Fig. 5. All cameras were tested with a

[3] Active Pixel Sensor

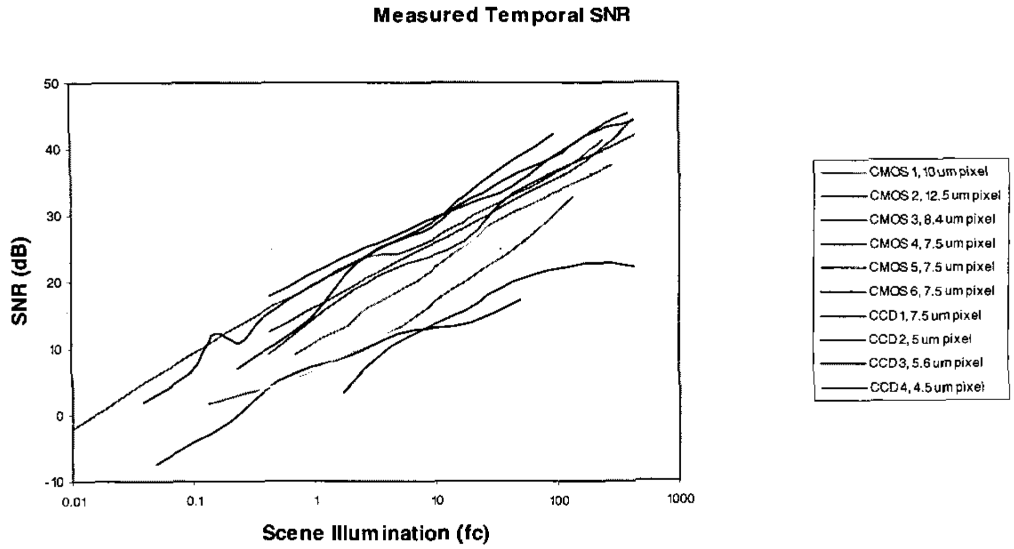

Figure 5. Measured SNR versus scene illumination for several CMOS and CCD cameras.

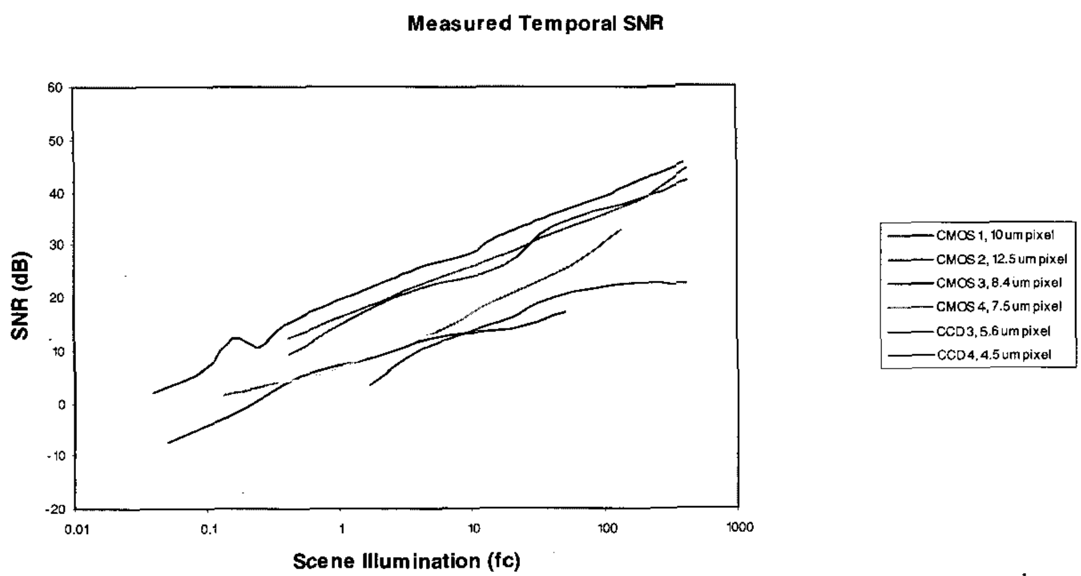

Figure 6. Pre-1999 CMOS sensors versus CCD.

fixed exposure of 8 ms, F/8 optics (1mm diameter aperture), and automatic or manual gain control. All of the measurements were normalized to a sensor with 7.5μm pixel size.

It is interesting to compare pre-1999 CMOS (Fig. 6) and post-2000 CMOS sensors (Fig. 7) versus CCD sensors. To eliminate clutter in the graphs and to emphasize the performance of CCD sensors with small pixels we show only two CCD cameras in Figs. 6 and 7.

As of the 1999 time frame CMOS technology was significantly inferior to CCD technology in sensitivity. Quantitatively, on average the CCD cameras have 15dB greater SNR compared to the CMOS cameras for a given illumination level. In addition, for a given SNR requirement

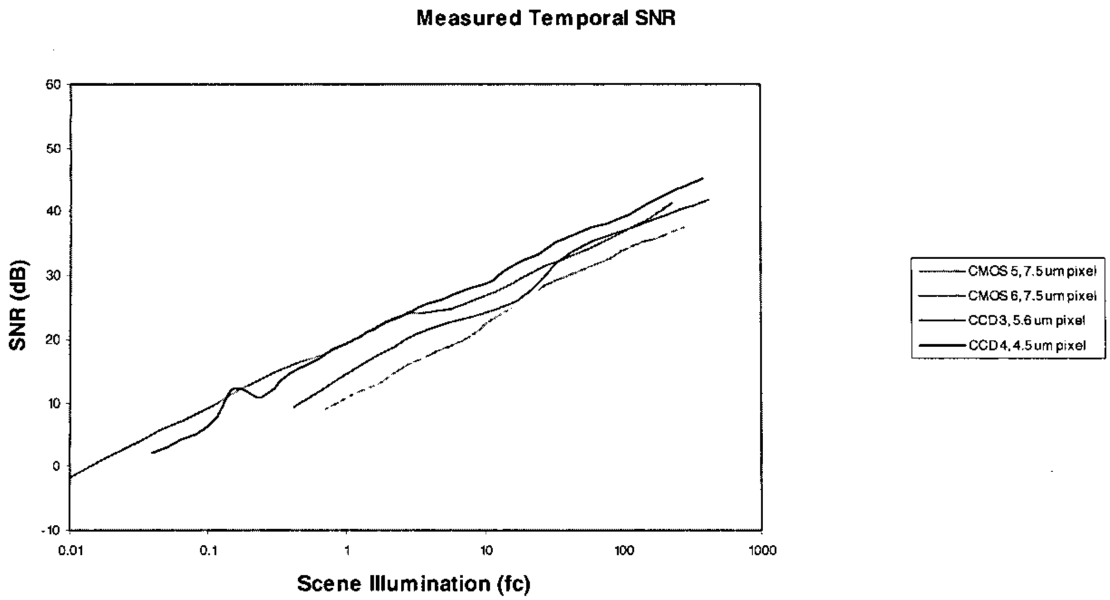

Figure 7. Post-2000 CMOS sensors versus CCD.

(constant SNR line in the figure) it takes roughly 10 times as much light to achieve it with a CMOS camera compared to a CCD camera. One exception was a CMOS sensor that had a relatively large pixel (CMOS 1, 10μm).

Two CMOS sensors (CMOS 5 and 6, Fig. 7) tested after 2000 have much improved SNR performance. One new CMOS sensor (CMOS 6) shows sensitivity performance comparable to CCD sensors, and another (CMOS 5) is significantly improved over the CMOS sensors of the 1999 time frame. The results presented here do not demonstrate that all CMOS sensor technologies have advanced to compete with CCDs in sensitivity; however, it is clear that CMOS and CCD cameras are converging to an indistinguishable camera system from the user or application point of view. Large variation in performance amongst CMOS sensor vendors may continue for several years.

CONCLUSIONS

We have presented an experimental method for measuring the sensitivity of digital cameras. The method is simple to implement and is accurate enough for the basis of sensor selection for consumer and industrial applications. The method is most suitable for comparing cameras with significantly different sensor architectures such as CCD and CMOS sensors.

Most CMOS sensor technologies have significantly less sensitivity than CCD technology; however, in recent years a few companies have made significant progress in the sensitivity of CMOS sensors. The cost and power dissipation of CCD sensors has decreased significantly in recent years, and the levels of integration have increased dramatically. One remaining distinction at this time is that CCD sensors can be made with significantly smaller pixels than CMOS. This means that CCD cameras can be made smaller than CMOS cameras because the focal length scales with the pixel size. As CMOS technology continues to improve this advantage for CCD will likely disappear. This suggests that in the near future there will be little differentiation between CCD and CMOS cameras.

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