CCD Sensor Primer

Radiant Imaging PM Series™ Imaging Photometers and Colorimeters utilise CCD sensors, and most models are available with a choice of different CCDs. In order to choose the right product configuration for a specific application, it is useful to have some understanding of what factors influence CCD performance.

CCD Architecture

CCDs (charge coupled devices) are monolithic semiconductor detector arrays. The CCD was first developed in the early 1970s as a computer memory device by Bell Labs. Incident photons are absorbed by the detector material and create electron-hole pairs. During exposure, electrons accumulate in each individual detector element, called a pixel, where they are held until the charge is read out. The total amount of charge that accumulates in each pixel is linearly proportional to the amount of light incident upon it.

There are a few basic forms of CCD architecture, with many variations for specific applications. Some Radiant Imaging PM Series™ Photometers and Colorimeters use full frame CCDs while others use interline transfer CCDs. In a full frame CCD, the entire detector surface is first exposed to light and then the light must be externally blocked off so that readout can occur without further charge accumulation during the readout process.

To detect the image stored in a full frame CCD, charge in each detector column is first shifted one row towards the serial register. The last row of charge goes into the serial register itself; this charge is then shifted one pixel at a time out of the serial register to produce an analogue signal. This process is repeated until all the accumulated charge has been read from the detector.

In an interline transfer CCD, alternate columns of the detector array are masked off with opaque material. To read out the image, the charge in each column of "light" pixels is simultaneously shifted into the adjacent "dark" column, which is blocked off from light. The stored image data can then be read out in the same way as described previously. However, new image information can be accumulated in the open pixels while this is occurring.

Interline transfer CCDs are usually relatively small arrays, and are produced in high volume for video camera applications. For these reasons, and because an interline transfer CCD does not need an external shutter to control exposure, cameras based on this technology are typically less costly than those using full frame CCDs. Interline transfer CCDs are also preferred in high speed applications because the data accumulation and readout processes can be occurring simultaneously. The major disadvantage of the interline transfer architecture is that part of the sensor surface is opaque, so it can not capture all the incident light. This lowers the quantum efficiency of the detector and also reduces the spatial resolution, even making it possible for small image features to be lost.

Full frame CCDs can be obtained in a large number of different array configurations. Scientific-grade devices refers to units that offer particularly high performance in terms of noise characteristics and the maximum allowable number of dead pixels. Full frame, scientific-grade CCD are the first choice for applications that require high quality, low noise imaging.

The drawback of full frame CCDs is that they require an external means of controlling exposure, typically a mechanical shutter. This increases camera cost, size and weight. Readout speed, which influences image noise, is also slower than for interline transfer CCDs.

Noise Sources

Noise limits the radiometric accuracy of CCD images. The primary noise sources in CCD detectors are thermal noise, read noise and shot noise.

Thermal noise

In addition to free electrons created by incident photons (called photoelectrons), thermal effects can also create free electrons. Image noise from this thermally created charge becomes particularly problematic at high temperatures, or during long exposures. Since thermal noise is extremely temperature dependent (every 6°C drop in temperature reduces it by a factor of two), cooling a CCD lowers this noise floor dramatically, and enables longer image integration times. Cooling is often used in low intensity or high dynamic range applications.

The most common cooling method for commercial CCD imagers is thermoelectric cooling (TEC). Depending upon the desired noise floor, this may be accomplished in several stages. For example, the first TEC cools the CCD itself, while the next is used to cool the first TEC's heat sink. This process can be extended.

Read Noise

Read noise is the uncertainty introduced into the signal during the process of reading out the pixels. This uncertainty occurs due to several factors. For example, reading out a pixel requires clearing out the charge in the pre-amplifier from the pixel that preceded it. However, it's possible that this reset operation may not occur completely or consistently, thus introducing some error.

Read noise is highly dependent upon readout speed. The faster the readout, the greater the noise.

Shot noise

The quantum nature of light causes the number of photons collected from a "constant" output light source to exhibit a statistical variation over time. This uncertainty in signal level, called shot noise, is equal to the square root of the number of photons collected in each pixel. Therefore, the higher the number of photoelectrons collected, the better the signal to noise ratio.

The maximum number of photoelectrons that each CCD pixel can accumulate is directly related to the pixel's physical size. Larger pixels can hold more electrons, and thus produce lower noise images.

Colour Accuracy

A CCD cannot distinguish between different wavelengths of light. Therefore, recording colour images requires that you separate the various wavelengths before they reach the CCD surface. There are several ways to accomplish this.

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On-Detector Filters

In this approach, a rectangular array (called a Bayer pattern) of red, green and blue colour filters is put directly onto the surface of an interline transfer CCD. The advantages of this method are low cost, small package size and mechanical ruggedness.

A drawback of this approach is that it reduces the fill factor of the CCD for each colour even further, making it possible to miss imaging small details. Also, the interline transfer CCDs typically used by device manufacturers have small pixels, which limits detector dynamic range. Colour accuracy is also badly compromised for non black body source because the filters used do not match well with CIE spectral responsivity curves. The lowered signal to noise ratio also compromises colour accuracy.

X-Cube Beamsplitter

This method uses a dichroic cube beamsplitter designed to separate the red, green and blue wavelengths and send them to three different interline transfer CCDs. Because all colours are detected simultaneously, this technique offers good read speed and is mechanically rugged. However, it is more costly and less compact than the Bayer array filter approach.

Because the commercially available product that uses this approach is based on interline transfer CCDs, it still suffers from limited fill factor and dynamic range. Most significantly, the thin film coatings used to separate wavelengths don't match well to CIE curves, making it difficult to achieve good colour accuracy.

Moving Filter Wheel

This technique mates a single, scientific grade, cooled, full frame CCD with a series of colour filters that are moved over the detector sequentially by a motorized filter wheel. An external shutter is necessary to block light from the detector between separate exposures. Depending upon the particular CCD chosen, this can deliver very high dynamic range, low noise, high spatial resolution and high fill factor. The filters can be chosen to deliver the best possible match to CIE responsivity curves. This approach also enables the use of other specialised wavelength filters

The disadvantages of this method are slower measurement times, higher cost and increased system size and weight.

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