CHARGE-COUPLED DEVICE (CCD)

Definition

A **charge-coupled device (CCD)** is an analog shift register, enabling analog signals, usually light, manipulation - for example, conversion into a digital value that can be recorded as a picture.

Basics

A charge-coupled device (CCD) is a device for the movement of electrical charge, usually from within the device to an area where the charge can be manipulated, for example conversion into a digital value. This is achieved by "shifting" the signals between stages within the device one at a time. Technically, CCDs are implemented as shift registers that move charge between capacitive bins in the device, with the shift allowing for the transfer of charge between bins.

Often the device is integrated with a sensor, such as a photoelectric device to produce the charge that is being read, thus making the CCD a major technology for digital imaging. Although CCDs are not the only technology to allow for light detection, CCDs are widely used in professional, medical, and scientific applications where high-quality image data is required.

History

The charge-coupled device was invented in 1969 at AT&T Bell Labs by Willard Boyle and George E. Smith. The lab was working on semiconductor bubble memory when Boyle and Smith conceived of the design of what they termed, in their notebook, 'Charge "Bubble" Devices'. The essence of the design was the ability to transfer charge along the surface of a semiconductor.

The first working CCD was an 8-bit shift register. As the CCD started its life as a memory device, one could only "inject" charge into the device at an input register. However, it was soon clear that the CCD could also accumulate charge via the photoelectric effect and electronic images could be created. By 1971, Bell researchers Michael F. Tompsett et al. were able to capture images with simple linear devices; thus the CCD imager was born.

Several companies, including Fairchild Semiconductor, RCA and Texas Instruments, picked up on the invention and began development programs. Fairchild's effort, led by ex-Bell researcher Gil Amelio, was the first with commercial devices, and by 1974 had a linear 500-element device and a 2-D 100 x 100 pixel device. Under the leadership of Kazuo Iwama, Sony also started a big development effort on CCDs involving a significant investment. Eventually, Sony managed to mass produce CCDs for their camcorders. Before this happened, Iwama died in August 1982. Subsequently, a CCD chip was placed on his tombstone to acknowledge his contribution.

In January 2006, Boyle and Smith were awarded the National Academy of Engineering Charles Stark Draper Prize, and in 2009 they were awarded the Nobel Prize for Physics, for their work on the CCD.

Basics of operation

In a CCD for capturing images, there is a photoactive region (an epitaxial layer of silicon), and a transmission region made out of a shift register (the CCD, properly speaking).

An image is projected through a lens onto the capacitor array (the photoactive region), causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. A one-dimensional array, used in line-scan cameras, captures a single slice of the image, while a two-dimensional array, used in video and still cameras, captures a two-dimensional picture corresponding to the scene projected onto the focal plane of the sensor. Once the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor (operating as a shift register). The last capacitor in the array dumps its charge into a charge amplifier, which converts the charge into a voltage. By repeating this process, the controlling circuit converts the entire contents of the array in the semiconductor to a sequence of voltages, which it samples, digitizes, and stores in memory.

Usage in color cameras

Digital color cameras generally use a Bayer mask over the CCD. Each square of four pixels has one filtered red, one blue, and two green (the human eye is more sensitive to green than either red or blue). The result of this is that luminance information is collected at every pixel, but the color resolution is lower than the luminance resolution.

Better color separation can be reached by three-CCD devices (3CCD) and a dichroic beam splitter prism, that splits the image into red, green and blue components. Each of the three CCDs is arranged to respond to a particular color. Some semi-professional digital video camcorders (and most professional camcorders) use this technique. Another advantage of 3CCD over a Bayer mask device is higher quantum efficiency (and therefore higher light sensitivity for a given aperture size). This is because in a 3CCD device most of the light entering the aperture is captured by a sensor, while a Bayer mask absorbs a high proportion (about 2/3) of the light falling on each CCD pixel.

For still scenes, for instance in microscopy, the resolution of a Bayer mask device can be enhanced by Microscanning technology. During the process of color co-site sampling, several frames of the scene are produced. Between acquisitions, the sensor is moved in pixel dimensions, so that each point in the visual field is acquired consecutively by elements of the mask that are sensitive to the red, green and blue components of its color. Eventually every pixel in the image has been scanned at least once in each color and the resolution of the three channels become equivalent (the resolutions of red and blue channels are quadrupled while the green channel is doubled).

Usage in astronomy

Due to the high quantum efficiencies of CCDs, linearity of their outputs (one count for one photon of light), ease of use compared to photographic plates, and a variety of other reasons, CCDs were very rapidly adopted by astronomers for nearly all UV-to-infrared applications. Thermal noise and cosmic rays may alter the pixels in the CCD array. To counter such effects, astronomers take several exposures with the CCD shutter closed and opened. The average of images taken with the shutter closed is necessary to lower the random noise. Once developed, the dark frame average image is then subtracted from the open-shutter image to remove the dark current and other systematic defects (dead pixels, hot pixels, etc.) in the CCD. The Hubble Space Telescope, in particular, has a highly developed series of steps (“data reduction pipeline”) to convert the raw CCD data to useful images. See the references for a more in-depth description of the steps in astronomical CCD image-data correction and processing.

CCD cameras used in astrophotography often require sturdy mounts to cope with vibrations from wind and other sources, along with the tremendous weight of most imaging platforms. To take long exposures of galaxies and nebulae, many astronomers use a technique known as auto-guiding.

Most autoguiders use a second CCD chip to monitor deviations during imaging. This chip can rapidly detect errors in tracking and command the mount motors to correct for them.

An interesting unusual astronomical application of CCDs, called drift-scanning, uses a CCD to make a fixed telescope behave like a tracking telescope and follow the motion of the sky. The charges in the CCD are transferred and read in a direction parallel to the motion of the sky, and at the same speed. In this way, the telescope can image a larger region of the sky than its normal field of view. The Sloan Digital Sky Survey is the most famous example of this, using the technique to produce the largest uniform survey of the sky yet accomplished.

In addition to astronomy, CCDs are also used in laboratory analytical instrumentation such as monochromators, spectrometers, and N-slit interferometers.

Source: http://www.juliantrubin.com/encyclopedia/electronics/ccd.html