1
INTRODUCTION

Charge-coupled devices (CCDs) were invented by Boyle and Smith[1,2] in 1970. Since then, considerable literature[3-10] has been written on CCD physics, fabrication, and operation. However, the array does not create an image by itself. It requires an optical system to image the scene onto the array's photosensitive area. The array requires a bias and clock signals. Its output is a series of analog pulses that represent the scene intensity at a series of discrete locations. While the photodetection process is analog, an analog-to-digital converter (either on-chip or off-chip) provides digital video.

Devices may be described functionally according to their architecture (frame transfer, interline transfer, etc.) or by application. Certain architectures lend themselves to specific applications. For example, astronomical cameras typically use full frame arrays whereas consumer video systems use interline transfer devices.

The heart of the solid-state camera is the solid-state array. It provides the conversion of light intensity into measurable voltage signals. With appropriate timing signals, the temporal voltage signal represents spatial light intensities. When the array output is amplified and formatted into a standard video format, a solid-state camera is created. Because CCDs were the first solid-state detectors, cameras were popularly called CCD cameras even though they may contain charge injection devices (CIDs) or complementary metal-oxide semiconductor (CMOS) devices as detectors. Now, these are commonly called solid-state cameras or simply digital cameras.

The array specifications, while the first place to start, are only part of the overall system performance analysis. The system image quality depends on all of the components. Array specifications, capabilities, and limitations are the basis for the camera specifications. Camera manufacturers cannot change these. A well-designed camera will not introduce additional noise nor adversely affect the image quality provided by the array.

A camera is of no use by itself; its value is only known when an image is evaluated. The camera output may be directly displayed on a monitor, stored on disk for later viewing, or processed by a computer. The computer may be part of a machine vision system, be used to enhance the imagery, or be used to create hard copies of the imagery. If interpretation of image quality is performed by an observer, then the observer becomes a critical component of the system. Consideration of human visual system attributes should probably be the starting point of camera design. But some industrial (machine vision) systems may not create a “user friendly” image. These systems are designed from a traditional approach: resolution, high signal-to-noise ratio, and ease of operation.

Effective camera design requires orderly integration of diverse technologies and languages associated with radiation physics, optics, solid-state sensors, electronic circuitry, and image processing algorithms. Each field is complex and is a separate discipline.

Electro-optical imaging system analysis is a mathematical construct that provides an optimum design through appropriate tradeoff analyses. A comprehensive model includes the target, background, properties of the intervening atmosphere, the optical system, detector, electronics, display, and human interpretation of the displayed information. While any of these components can be studied in detail separately, the electro-optical imaging system cannot.

1.1. SOLID-STATE DETECTORS

CCD refers to a semiconductor architecture in which charge is read out of storage areas. The CCD architecture has three basic functions: a) charge collection, b) charge transfer, and c) conversion of the charge into a measurable voltage. The basic building block of the CCD is the metal-oxide semiconductor (MOS) capacitor. The capacitor is called a gate. By manipulating the gate voltages, charge can be either stored or transferred. Charge generation in most devices occurs under a MOS capacitor (also called a photogate). For some devices (notably interline transfer devices), photodiodes create the charge. After charge generation the transfer occurs in the MOS capacitors for all devices.

Because most sensors operating in the visible region use CCD-type architectures to read the signal, they are popularly called CCD cameras. For these devices, charge generation is often considered as the initial function of the CCD. More explicitly, these cameras should be called solid-state cameras with a CCD readout. As film-based cameras are replaced by digital still cameras, they are simply referred to as a camera with “digital” understood.

CCDs and detectors can be integrated either monolithically or as hybrids. Monolithic arrays combine the detector and CCD structure on a single chip. The most common detectors are sensitive in the visible region of the spectrum. They use silicon photogates or photodiodes and are monolithic devices. CCDs have been successfully used for infrared detectors such as Schottky barrier devices that are sensitive to radiation in the 1.2 to 5 μm spectral region.

Hybrid arrays avoid some pitfalls associated with growing different materials on a single chip and provide a convenient bridge between well-developed but otherwise incompatible technologies. HgCdTe (sensitive to 8 to 12 μm radiation) is bump bonded to a CCD readout using indium as the contact and, as such, is a hybrid array.

With charge-injection devices (CIDs), the pixels consist of two MOS capacitors whose gates are separately connected to rows and columns. Usually the column capacitors are used to integrate charge, while the row capacitors sense the charge after integration. With the CID architecture, each pixel is addressable: it is a matrix-addressable device.

CID readout is accomplished by transferring the integrated charge from the column capacitors to the row capacitors. After this nondestructive signal readout, the charge moves back to the columns for more integration or is injected (discarded) into the silicon substrate. By suspending charge injection, the user initiates "multiple frame integration" (time lapse exposure) and can view the image on a display as the optimum exposure develops. Integration time may be up to several hours. Since each sensing pixel has its own capacitor, saturation will not spill over into neighboring pixels (minimal blooming).

In the 1990s, active pixels[11-14] were introduced. These devices are fabricated with readily available CMOS technology. The advantage is that one or more active transistors can be integrated into the pixel. Now, system-level circuit elements can be integrated inside a pixel cell to perform on-chip image processing. These are also called active pixel sensors or APS detectors. They are fully addressable (can read selected pixels) and can perform on-chip image processing. CMOS imager sensors (CIS) typically use less than one-tenth of the power consumed by CCD imagers with the same function and resolution. Most digital cameras contain CMOS detectors. CMOS and CCD operation is quite different.[15-19]

1.2. IMAGING SYSTEM APPLICATIONS

There are four broad applications for imaging systems: general imagery (includes professional TV broadcast, consumer camcorder systems, and digital still cameras); industrial (includes machine vision); scientific; and military. Trying to appeal to all four applications, manufacturers use words such as low noise, high frame rate, high resolution, reduced aliasing, and high sensitivity. These words are simply adjectives with no specific meaning. They only become meaningful when compared (e.g., camera A has low noise compared to camera B).

Table 1-1 lists several design categories. While the requirements vary by category, a camera may be used for multiple applications. For example, a consumer video camera is often adequate for many scientific experiments. A specific device may not have all the features listed or may have additional ones not listed. The separation between professional broadcast, consumer video, industrial (machine vision) scientific, and military devices becomes fuzzy as technology advances.

Color cameras are used for professional TV, camcorder, and film replacement systems (digital still cameras). With machine vision systems, color cameras are used to verify the color consistency of objects such as printed labels or paint mixture colors. While color may not be the primary concern, it may be necessary for image analysis when color is the only information to distinguish boundaries. While consumers demand color camera systems, this is not true for other applications. Depending on the application, monochrome (black and white) cameras may be adequate. A monochrome camera has higher sensitivity and therefore is the camera of choice in low-light conditions.

Image enhancement helps an observer extract data. Some images belong to a small precious data set (e.g., remote sensing imagery from interplanetary probes). The images must be processed repeatedly to extract every piece of information. Some images are part of a data stream that is examined once (e.g., real-time video) and others have become popular and are used routinely as standards. These include the three-bar or four-bar test patterns, Lena, and the African mandrill.

The camera cannot perfectly reproduce the scene. The array spatially samples the image and noise is injected by the array electronics. Spatial sampling creates ambiguity in target edge location and produces moiré patterns when viewing periodic targets. While this is a concern to scientific and military applications, it typically is of little consequence to the professional broadcast and consumer markets.

To some extent the goals listed in Table 1-1 are incompatible, thereby dictating design compromises. The demand for machine vision systems is increasing dramatically. Smaller target detail can be discerned with magnifying optics. However, this reduces the field of view. For a fixed field of view, higher resolution (more pixels) cameras are required to discern finer detail.

Table 1-1
DESIGN GOALS

Design Category	General Imagery	Industrial	Scientific	Military
Image processing algorithms	Gamma correction Extended dynamic range	Application specific	Menu-driven multiple options	Application specific
Image processing time	Real time	Application-specific with emphasis on high speed operation	Real-time not usually required	Real time
Resolution	Matched to video format (e.g., EIA 170)	For a fixed field of view, increased resolution is desired	High resolution	High resolution
Dynamic range	8 bits/color	Up to 10 bits/color or black and white	Up to 16 bits	Up to 16 bits
Sensitivity (high signal-to-noise ratio)	High-contrast targets (noise not necessarily a dominant design factor)	Application-specific (not necessarily an issue because lighting can be controlled)	Low-noise operation	Low-noise operation

Table 1-2 separates the designs by overall performance "quality." It is relatively easy to classify "high end" and "low end" but "medium" falls somewhere between. Camera selection depends on the application. In many situations a medium-performance camera suffices. When selecting an imaging system, the environment, camera, data storage, and final image format must be considered (Table 1-3).

Table 1-2
GENERAL CHARACTERISTICS
"Medium" is ill-defined. It could be a very good low quality or an 'average' high quality camera.

Performance quality	Application	Array size	Pixel size	Performance metrics/ design
High	Industrial Scientific Military	Up to 100 Mpixels	Greater than 10 µm	Large well capacity. Large dynamic range High SNR High quantum efficiency (may be back-illuminated)
Medium				
Low	General imaging (Consumer)	Less than 20 Mpixels	Less than 10 µm	Small well capacity Small dynamic range Low SNR Usually front illuminated

Table 1-3
SYSTEM DESIGN CONSIDERATIONS

Environment	Camera	Transmission and Storage	Display
Target size Target reflectance Distance to target Atmospheric transmittance Lighting conditions	Noise Frame rate Sensitivity Detector size Array format Dynamic range Color capability	Data rate Type of storage Storage capacity Video compression	Hard copy Soft copy Resolution

Finally, the most convincing evidence of system performance is image quality. Every time an image is transferred to another device, that device's tonal transfer and modulation transfer function (MTF) affect the displayed image. Analog video recorders degrade resolution. Imagery will look different on different displays. Similarly, hard copies produced by different printers may appear different, and there is no guarantee that the hard copy will look the same as the soft copy in every respect. Hard copies should only be considered as representative of system capability. Even with its over 100-year history, wet-film developing and printing must be controlled with extreme care to create "identical" prints.

1.2.1. GENERAL IMAGERY

Cameras for the professional broadcast TV and consumer camcorder markets are designed to operate in real time with an output consistent with a standard broadcast format. The resolution, in terms of array size, is matched to the bandwidth recommended in the standard. An array that provides an output of 768 horizontal by 484 vertical pixels creates a satisfactory image for conventional television. Current high-definition TV requires 1920×720 pixel 60 Hz cameras (or 1920×1080 pixel 50 Hz cameras). Eight bits (256 intensity levels or gray levels) provide an acceptable image in the broadcast and camcorder industry. The largest consumer application is the mobile phone market. Second are the camcorder and digital still camera markets. With the desire to make cell phones and consumer cameras smaller, detector sizes are shrinking. The pixel size in many cell phones is only 2.2 μm. Future phones will have 1.75 μm pixels, with the desire to reach 1.4 μm. As the pixel sizes decreases, the charge well capacity decreases, the signal-to-noise decreases, and crosstalk between adjacent pixels increases.

CMOS sensors have advantages compared to CCDs: lower power consumption, lower cost, and greater radiation hardness. However, CCDs are the choice for very high-end applications such as astrometry, medical imaging, professional cameras, and scientific applications.

Because solid-state cameras have largely replaced image vacuum tubes, the terminology associated with these tubes is also used with solid-state cameras. However, compared to image vacuum tubes, solid-state cameras have no image burn-in, no residual imaging, and usually are not affected by microphonics.

1.2.2. INDUSTRIAL (MACHINE VISION)

In its simplest version, a machine vision system consists of a light source, camera, and computer software that rapidly analyzes digitized images with respect to location, size, flaws, and other preprogrammed data. Unlike other types of image analysis, a machine vision system also includes a mechanism that immediately reacts to images that do not conform to the parameters stored in the computer. For example, defective parts are taken off a production conveyor line.

Machine vision functions include location, inspection, gauging, counting, identification, recognition, and motion tracking. These systems do not necessarily need to operate at a standard frame rate. For industrial inspection, linear arrays operating in the time delay and integration (TDI) mode can be used to measure objects moving at a high speed on a conveyor belt.

While a multitude of cues are used for target detection, recognition, or identification, machine vision systems cannot replace the human eye. The eye processes intensity differences over 11 orders of magnitude, color differences, and textual cues. The solid-state camera, on the other hand, can process limited data much faster than the human. Many operations can be performed faster, cheaper, and more accurately by machines. Machine vision systems can operate 24 hours a day without fatigue. They operate consistently, whereas variability exists among human inspectors. Further, these cameras can operate in harsh environments that may be unfriendly to humans (e.g., extreme heat, cold, or ionizing radiation).

1.2.3. SCIENTIFIC APPLICATIONS

For scientific applications, low noise, high responsivity, large dynamic range, and high resolution are dominant considerations. To exploit a large dynamic range, scientific cameras may digitize the signal into 12, 14, or 16 bits (sometimes listed as 12-b, 14-b, and 16-b respectively). Array linearity and analog-to-digital converter linearity are important. Resolution is specified by the number of detector elements, and scientific arrays may have 10,000×10,000 detector elements.[20] Theoretically the array can be any size, but manufacturing considerations may ultimately limit the array size.[21] Very large sensors are possible by butting together smaller arrays. The Gaia satellite, set to launch in 2012, will have 206 butted CCD arrays each with 4500×1966 pixels, for a total of 937.8 million pixels.

Transitory events can only be captured with high-frame-rate cameras. CCD cameras are approaching[22] 10^6 frames per second. To minimize the output amplifier bandwidth, the array consists of four 100×489 pixel subarrays. Since output signal is proportional to the integration time (t_{INT} ~ 1 μs), electron multiplying pixels (EMCCD) are added to compensate for the low sensitivity. The EMCCD multiplies the charge prior to readout and is a noiseless process.

Low noise means low dark current and low readout noise. The dark current can be minimized by cooling the CCD. Long integration times can increase the signal value so that the readout noise is small compared to the photon shot noise. Although low-light-level cameras have many applications, they tend to be used for scientific applications. There is no industry-wide definition of a "low light level" imaging system. To some, it is simply a solid-state camera that can provide a usable image when the lighting conditions are less than 1 lux. To others, it refers to an intensified camera and is sometimes called a low-light-level TV (LLLTV) system. An image intensifier amplifies a low-light image sensed by a solid-state camera. The image-intensifier/CCD camera combination is called an intensified CCD, ICCD, or I2CCD. The image intensifier provides tremendous amplification but also introduces additional noise.

1.2.4. MILITARY APPLICATIONS

The military is interested in detecting, recognizing, and identifying targets at long distances. This requires high-resolution, low-noise sensors. Target detection is a perceptible act. A human determines if the target is present. The military uses the minimum resolvable contrast (MRC) as a figure of merit.

Solid-state cameras are popular because of their ruggedness and small size. They can easily be mounted on remotely piloted vehicles. They have replaced wet-film systems for mapping and photo interpretation.

1.3. CONFIGURATIONS

Imaging systems for the four broad application categories may operate in a variety of configurations. The precise setup depends on the specific requirements. Figure 1-1 is representative of a CCTV system where the camera output is continuously displayed. The overall image quality is determined by the camera capability (which is based on the array specifications), the bandwidth of the video format (e.g., EIA 170, NTSC, PAL, or SECAM), display performance, and the observer. EIA 170 was formerly called RS 170, and the NTSC standard is also called RS 170A. These formats have been replaced with high-definition TV (HDTV) format.

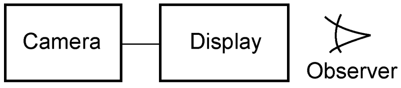

Figure 1-1. A closed circuit television system. Image quality is determined by an observer.

Figure 1-2 illustrates a generic transmission system. The transmitter and receiver must have sufficient electronic bandwidth to provide the desired image quality. For remote sensing, the data may be compressed before the link. Compression may alter the image, and the effects of compression will be seen on selected imagery. Compression effects are not objectionable in most imagery.

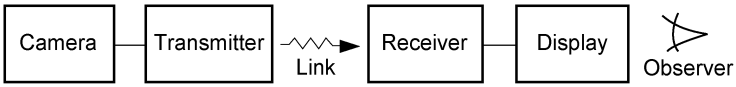

Figure 1-2. Generic remote transmission system. The transmitter and receiver must have adequate electronic bandwidth to support the image quality created by the solid-state camera. Conventional TV had used analog transmission, now replaced by digital transmission.

For remote applications, the image may be recorded on a separate video recorder[23,24] (Figure 1-3) or with a camcorder. The recorder further modifies the image by reducing the signal-to-noise ratio (SNR) and image sharpness. Initially, all camcorders used tape, and the most popular player was the video cassette recorder (VCR). As the desire for portability increased, cameras and recorders shrank in size, and digital flash memories and DVD players replaced VCRs.

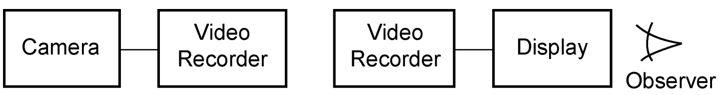

Figure 1-3. Imagery can be stored on analog video tape. However, the recorder circuitry may degrade the image quality. Digital storage has replaced the analog tape.

For scientific applications, the camera output is digitized and then processed by a computer (Figure 1-4). After processing, the image may be presented on a monitor (soft copy), printed (hard copy), or stored. The digital image can also be transported to another computer via the Internet, local area network, CD/DVD, or memory stick. For remote applications, the digital data may be stored on a digital recorder (Figure 1-5).

Perhaps the most compelling reason for adopting digital technology is the fact that the quality of digital signals remains intact through copying and reproduction unless the signals are deliberately altered. Digital signal "transmission" was first introduced into tape recorders. Because a bit is either present or not, multiple-generation copies retain high image quality.

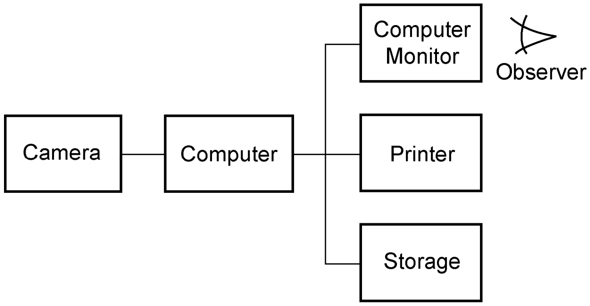

Figure 1-4. Most imagery today is enhanced through image processing. The camera may view a scene directly or may scan a document. The computer's output hard copy may be used in all forms of print media.

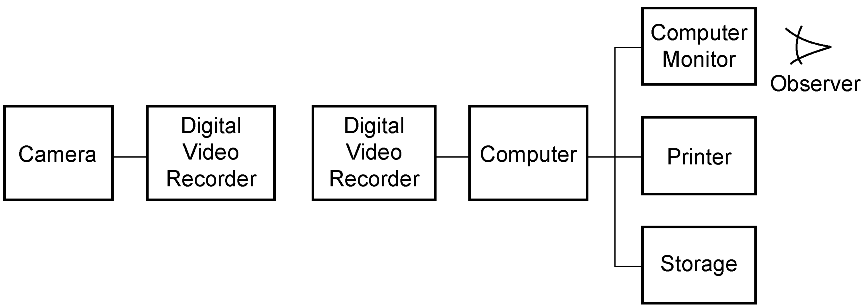

Figure 1-5. Digital systems can provide very high-quality imagery. Electronic bandwidth limitations may impose data compression requirements. Data compression may alter the image, but the alteration may not be obvious in general imagery.

In comparison, analog recorders such as the video home system (VHS) provide very poor quality after just a few generations. The first digital recorder used a format called D-1, which became known as the CCIR 601 component digital standard. Digital recording formats now include[23] D-1, D-2, D-3, D-4, D-5, and D-6. This has been upgraded to D-7. Error-correcting codes can be used to replace missing bits.

New digital recorders[25,26] combine advanced technologies in electronics, video compression, and mechanical transport design. Real-time digital video systems operate at data rates that are faster than many computers. While errors in the imagery are never considered desirable, the eye is very tolerant of defects. In comparison, a computer is considered worthless if the error rate is high.

When it comes to displaying images (either hard copy or soft copy), the dynamic range of the camera digitizer is often greater than the display device. A camera may offer 12, 14, or 16 bits whereas the display may only be 8 bits. Here, a look-up table is used to match the camera output to the display. This may be a simple linear relationship or specific expansion of a part of the camera's gray scale. The greatest challenge is matching the camera's dynamic range to the scene dynamic range and converting this range into the limited display dynamic range.

While a machine vision system does not require a monitor (Figure 1-6), a monitor is often used during system setup and for diagnostic evaluation. A computer algorithm compares an image to a stored standard. If the target does not compare favorably to the standard, then the process is changed. For example, this may mean sending a rejected item for rework.

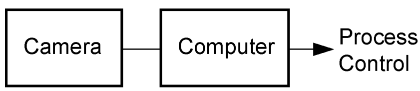

Figure 1-6. Machine vision systems do not require a monitor. The computer output controls the manufacturing process. Monitors are used for setup and diagnostic evaluation.

1.4. IMAGE QUALITY

Image quality is a subjective impression of ranking imagery from poor to excellent. It is a somewhat learned skill. It is a perceptual ability, accomplished by the brain, affected by and incorporating other sensory systems, emotions, learning, and memory. The relationships are many and not well understood. Perception varies between individuals and over time. There exist large variations in an observer's judgment as to the correct rank ordering from best to worst and therefore image quality cannot be placed on an absolute scale. Visual psychophysical investigations have not measured all the properties relevant to imaging systems.

Many formulas exist for predicting image quality. Each is appropriate under a particular set of viewing conditions. These expressions are typically obtained from empirical data in which multiple observers view many images with a known amount of degradation. The observers rank order the imagery from worst to best and then an equation is derived that relates the ranking scale to the amount of degradation.

Early metrics were created for film-based cameras. Image quality was related to the camera lens and film modulation transfer functions (MTFs). With the advent of television, image quality centered on the perception of raster lines and the minimum SNR required for good imagery. Here, it was assumed that the studio camera provided a perfect image and only the receiver affected the image quality.

The system MTF is the major component of system analysis. It describes how sinusoidal patterns propagate through the system. Because any target can be decomposed into a Fourier series, the MTF approach indicates how imagery will appear on the display.

Many tests have provided insight into image metrics related to image quality. Most metrics are related to the system MTF, resolution, or the signal-to-noise ratio. In general, images with higher MTFs and less noise are judged as having better image quality. There is no single ideal MTF shape that provides the best image quality.

Digital processing is used for image enhancement and analysis. Because the pixels are numerical values in a regular array, mathematical transforms can be applied to the array. The transform can be applied to a single pixel, group of pixels, or the entire image. Many image processing designers think of images as an array of numbers that can be manipulated with little regard to how the data will be used (viewed by an observer on a monitor, printed, or machine vision).

With a solid-state camera system, the lens, array architecture, array noise, and display characteristics all affect system performance. Only an end-to-end assessment will determine the overall image quality. There is no advantage to using a high-quality camera if the display cannot produce a faithful image. Often, the display is the limiting factor in terms of image quality and resolution. No matter how good the camera, if the display resolution is poor, the overall system resolution is poor. Only if the display's contrast and spatial resolution are better than the camera will the camera's image quality be preserved.

For consumer applications, system resolution is important and SNR is secondary. Scientific applications may place equal importance on resolution and MTF. The military, interested in target detection, couples the system MTF and system noise to create a perceived contrast. When the perceived contrast is above a threshold value, the target is just detected. The contrast at the sensor's entrance aperture depends on the range and atmospheric transmittance.

1.5. PIXELS, DATELS, DISELS, and RESELS

The overall system may contain several independent sampling systems. The array spatially samples the scene, the computer may have its own digitizer, and the monitor may have a limited resolution. A monitor "pixel" may or may not represent a "pixel" in camera space. The designer and user must understand the differences among the sampling lattices.

Sampling theory describes the requirements that lead to the reconstruction of a digitized signal. The original analog signal is digitized, processed, and then returned to the analog domain. For electrical signals, each digitized value is simply called a sample and the digitization rate is the sampling rate.

Electronic imaging systems are more complex, and several sampling lattices are present. The detector output represents a sampling of the scene. The detector output voltage is digitized and placed in a memory. After image processing, the data are sent to a display medium. We cannot see digital data. The display medium converts it into an analog signal. Note that the display electronics are typically digitally controlled (hence called a digital display).

Each device has its own minimum sample size or primary element. Calling a sample a pixel or a pel (picture element) does not seem bad. Unfortunately, there is no *a priori* relationship between the various device pixels. The various digital samples in the processing path are called pixels, datels, and disels (sometimes called dixels) (Table 1-4 and Figure 1-7). There is no standard definition for a resel. When a conversion takes place between the analog and digital domains, the resel may be different from the digital sample size. The analog signal rather than the digital sample may limit the system resolution. In oversampled systems, the resel consists of many samples.

Table 1-4
THE "-ELS"

Element	Description
Pixel or pel (picture element)	A sample created by a detector.
Datel (data element)	Each datum is a datel. Datels reside in a computer memory.
Disel (display element)	The smallest element (sample) that a display medium can access.
Resel (resolution element)	The smallest signal supported by an analog system

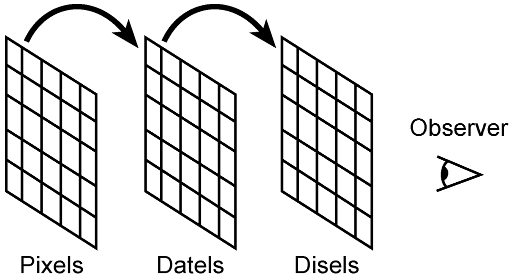

Figure 1-7. Each array is mapped onto the next. The number of elements in each array may be different.

For staring arrays, the total number of pixels is equal to the number of detectors. The detector's spatial response is determined by the detector's photosensitive area, whereas sampling depends on the center-to-center spacing (pitch). If the photosensitive extent is d_H in the horizontal direction (d_V in the vertical direction) and the optics focal length is fl, then the detector angular subtenses (DASs) are

$$DAS_H = \frac{d_H}{fl} \quad and \quad DAS_V = \frac{d_V}{fl} \tag{1-1}$$

Staring arrays are often specified by the detector pitch. The pixel angular subtenses (PASs) are

$$PAS_H = \frac{d_{CCH}}{fl} \quad and \quad PAS_V = \frac{d_{CCV}}{fl} \tag{1-2}$$

where $\mathbf{d}_{\mathbf{CCH}}$ and d_{CCV} are the horizontal and vertical pitches, respectively. The fill factor (Figure 1-8) is the ratio of areas

$$Fill\ factor = \frac{d_H\ d_V}{d_{CCH}\ d_{CCV}} = \frac{A_D}{A_{PIXEL}} \tag{1-3}$$

With a staring array that has a 100% fill factor, the PAS is equal to the DAS (i.e., $d_H = d_{CCH}$ and $d_V = d_{CCV}$).

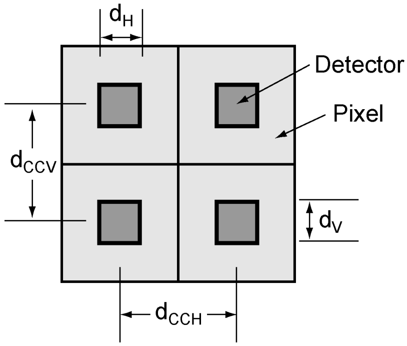

Figure 1-8. Fill Factor definition. The photosensitive area (A_D) is $d_H d_V$ and the pixel area (A_{PIXEL}) is $d_{CCH} d_{CCV}$.

If the Airy disk (a resel) is much larger than the PAS, then the optical resel determines the system resolution. If the electronic imaging system output is in a digital format, then the number of datels (samples) equals the number of pixels. If the camera's analog output is digitized, then the number of datels is linked to the frame grabber's digitization rate. This number can be much greater than the number of pixels. This higher number does not create more resolution in terms of the "-els."

Image processing algorithms operate on datels. A datel may not represent a pixel or a resel. Because there must be two samples to define a frequency, the Nyquist frequency associated with pixels, datels, and disels may be different. If there are more datels than pixels, the Nyquist frequency associated with an image processing algorithm is higher than that for the detector array. Most image processing books illustrate datels and call them pixels. The image processing specialist must understand the differences between the sampling lattices and take into account who will be the final data interpreter.

After image processing, the datels are outputted to a display medium. For monitors, each datel is often mapped, one-to-one, onto each disel. Monitors are often specified by the number of addressable pixels (defined as disels in this text). Consider a printer that provides 600 dpi. If the number of pixels is 640×480 and there were one-to-one mapping, the image size would be approximately 1 inch square. Obviously there is a one-to-many mapping with printers.

Finally, the system designer must be aware of which subsystem limits the overall system resolution. In some respects, the starting point for system design should begin with the final interpreter of the data. The minimum "-el" should be just discernible by the interpreter to ensure maximum transfer of information. However, the observer may not find this image aesthetically pleasing.

1.6. REFERENCES

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