4 Keys to Maximizing Digital Image Capture

This installment covers specific types of digital cameras available and ancillary equipment that should be considered to maximize the digital camera's performance in your machine vision application.

1. Types of cameras: area array

Area cameras are often used to capture images of stationary objects or objects that move in more than one dimension. The image is provided to the camera as a series of lines composing a frame, and the camera generates a separate signal indicating the start and end of the frame. Common applications for area array cameras include pick and place machines, motion analysis, and lead inspection. Images from an area scan camera will not suffer from blurring as long as object's motion during the exposure period of the sensor array is not significant.

When considering digital cameras, it is very likely that, if the camera is an area scan device, it will provide a progressively scanned image that is presented as consecutive lines of data. Progressive scanning eliminates artifacts that can result from interlacing the image and thus is desirable for machine vision applications. (When a frame is composed of two intertwined fields of alternating even and off lines, it is called an interlaced display).

CCD (Charged Coupled Device): A CCD sensor consists of an array of photosensitive areas and adjoining capacitors for storing the accumulated charge.

Many cameras incorporate features that allow for increased frame rates but sacrifice resolution. One feature available in CCD cameras that overcomes this limitation is binning, in which values of adjacent pixels are summed together into a single pixel. This allows reduced resolution images while increasing the apparent responsiveness of the camera. As an example, if a 1024x1024 resolution camera is binned two times vertically and two times horizontally, each 2x2 section of the sensor is reduced to a single pixel. The overall resolution of the image will then be 512x512, resulting in a four times reduction of the frame size, and a four times increase in responsivity, assuming the sensor doesn't reach saturation.

Typically, one of three sensor architectures is used in a progressive scan camera with CCD sensor technology:

• **Interline Transfer (ILT)** is the most common architecture. In interline transfer technology, the accumulated charges on the sensor's capacitors are transferred on a line-by-line basis to a readout register. Once the charges are read out, the remaining lines are shifted down. Think in terms of a bucket brigade!

While ILT is suitable for most low-end applications, it suffers from poor fill factors (approximately 30%). This is not adequate for most high-end applications, since details can literally fall between the cracks. To compensate for their poor fill factor, some ILT devices contain individual lenses on each pixel that focus most of the light onto the active part of the pixel region.

• **Full frame arrays** are simply arrays of pixels that are exposed and then transferred directly from the active region. The advantage of full frame technology is that it provides a 100% fill factor and is an effective use of the silicon.

The disadvantage is that the light illuminating the sensor must be blocked during frame readout, either with a shutter (mechanical/LCD) or by strobing the light source to avoid image smear. If strobing or shuttering is not possible, the exposure time must be significantly longer than the frame readout time of the camera to minimize smear to an acceptable level.

• **Frame transfer arrays** consist of the active array of pixels and a storage region. Once the image is exposed onto the active array and following exposure, it is transferred to the storage region, which is the same size as the active area but is covered with a light shield to prevent further exposure of the acquired image.

The major advantages of this technology are that no shutter is required and it provides a 100% fill factor. The major disadvantage is that twice as much silicon is needed when compared to full frame sensors. For example, in a 1K sensor, the charge is accumulated in 1024x1024 pixels during the integration period. The charge accumulated in the imaging region is then quickly transferred to the storage region, an additional 1024x1024 region that is not light sensitive. From there, the frame is read out while the next frame is being integrated. No shutter is normally required because the amount of time that it takes to transfer the charge to the storage region is typically less than 1% of the frame period and, therefore, the smearing would be less than 1%.

Some exceptions should be taken into consideration. If an exposure signal were used to shorten the integration time (exposure control), then the amount of smearing would increase. For example, if the time it takes to move the charge from the imaging region to the storage region is 1ms and exposure control is used so that the integration time is only 1ms, a 50% smearing would occur and the image would be useless. In this case, it would be necessary to use a strobed light source (since shutter speeds are too slow—typically, 10ms and up) to turn off the light while the image is transferred to the storage region. The following formula can be used to help decide when a shutter or strobed light source is required.

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Amount of image smear = (frame transfer time/(Integration time * frame transfer time)) *100

If the object being imaged moves during integration of the frame, the image may then look blurry. Blur can be minimized by using a faster frame rate or by using the exposure signal at the cost of sensitivity and additional smearing (in which case strobed light may be required).

CMOS (Complementary Metal Oxide Semiconductor):
While CMOS sensors typically do not have the same low noise characteristics that CCD sensors do, their signal-to-noise ratio is improving, and CMOS has several significant benefits over CCD. These include: high speed, resistance to blooming (meaning that the charge accumulated on a pixel can leak to adjacent areas if the charge is too great, which may occur if a CCD sensor is saturated), and low power consumption.

Unlike CCD sensors, CMOS sensors can be addressed randomly, which easily allows an ROI (region of interest) readout of the image. CMOS cameras can increase frame rates by allowing the user to select a region of interest within the overall image and sending only that region out. As an example, a CMOS camera may have a total sensor resolution of 1024x1024 pixels. The CMOS camera has the capability of selecting the pixel addresses to be sent out. If the entire array is required, then the addresses selected will be 0,0 and 1023,1023. The user may decide to select a portion of the image, such as 300,200 and 700,600, to be sent from the camera. The camera will then send only the selected lower resolution portion of the overall image, at a much faster frame rate.

Overall, CMOS sensor technology has several advantages over CCD technology, but, to date, the factor limiting wide acceptance has been lower image quality due to higher noise levels, due to amplifiers required at each pixel location, and hot pixels. Hot pixels are single pixels that suffer from significant leakage current compared to neighboring pixels, such that in dark these pixels are elevated compared to neighboring pixels. Additionally, because of the extra circuitry at each location, the fill factor is lower than for many CCD technologies (full frame CCD provides a 100% fill factor).

2. Types of cameras: line scan

Up to this point, only area array cameras have been considered. Line scan cameras are the technology of choice when the object and camera are moving relative to one another.

Line scan and high sensitivity line scan cameras are well suited to applications where the objects being imaged are in motion and are moving in only one dimension. Typical examples of line scan applications include web inspection, flat panel display inspection, bottle inspection, and postal/parcel sorting.

Many applications that currently use analog RS-170-based area scan cameras are also well suited for line scan cameras, including, most notably, printed circuit board inspections. Currently, many PCB inspection systems use lower resolution, RS-170-based cameras that must be moved to take two-dimensional snapshots of different sections of the board until the entire board has been imaged. Each snapshot requires moving the camera, stopping the camera, and allowing it to integrate a frame. This requires blocking off the light to the sensor while the camera is moving, either by using a strobe or a shutter. With multiple line scan cameras usually the entire PCB can be imaged with one continuous pass while obtaining a much higher resolution image with constant illumination. Additionally, because the high-resolution image is continuous, there is no need to join the frames together as would be required in the area scan case described.

Because line scan cameras employ a linear array, much higher resolutions and image sizes become economically possible. For example, area scan cameras with resolutions of 4K pixels in the horizontal axis are currently fairly uncommon and very expensive, while these resolutions and up to 12k pixel counts are quite common in line scan cameras.

Line scan cameras can also adapt easily to applications where the illumination is constant but the speed of the web or object being imaged varies. In such situations, the exposure control feature can act as an electronic shutter to allow exposure and line rate to be independent.

High sensitivity line scan cameras are not a good option when web speed varies unpredictably because it is not possible to control exposure with these cameras. In some applications where high sensitivity is required, binning can be used at the cost of lowered resolution. When binning, a camera combines the charge collected by two or more pixels. Not all cameras come with binning as a standard feature, which should be kept in mind when choosing a line scan camera.

High sensitivity line scan cameras should be chosen for applications that require higher sensitivity, higher speeds, or lower light. Typical examples of high sensitivity line scan applications include wafer inspection, flat panel display inspection, high-speed document scanning, and fluoroscopy, in which light hits an object and the object fluoresces at a particular wavelength of light. Because the light emitted from the sample has such a narrow bandwidth, the broadband optical power is very small, thus requiring a high sensitivity line scan camera.

The main benefit of high sensitivity line scan cameras is their responsivity compared to line scan cameras. High sensitivity line scan cameras responsivity is orders of magnitude higher than line scan. Utilizing TDI (Time, Delay and Integration) technology, high sensitivity line scan cameras accumulate multiple exposures of the same (moving) object, effectively increasing the integration time available to collect incident light. The number of exposures is directly related to the numbers of stages on the TDI sensor. Some cameras have the ability to use less than their maximum number of stages through stage selectability.

Bi-directional high sensitivity line scan cameras are often preferable for applications in which the camera must make several passes over a wide imaging region in a serpentine-like fashion. Unlike unidirectional high sensitivity cameras, bi-directional high sensitivity cameras do not have to be physically turned to make successive passes.

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Horizontal or vertical binning also may be an option on high sensitivity line scan cameras. Another factor to keep in mind with high sensitivity line scan cameras is that, if the motion of the object being scanned is not perpendicular to the camera, image quality will be degraded, because the image seen by the first stage will be different than the image seen by the last stage. Line scan cameras (with single line sensors) are far less susceptible to this effect. High sensitivity line scan cameras require greater care in aligning the camera and/or the web transport mechanism in the system. Some high sensitivity line scan cameras can be operated in an area scan mode for ease of camera alignment with the web transport.

High sensitivity line scan cameras also require constant object speeds, so they may not be appropriate for applications such as imaging peas or ball bearings rolling on a conveyer belt, where the velocity of the object continually changes. Some applications require several cameras to image across a wide web. Multi-camera synchronization capability may be necessary to synchronize the data readout from each camera. Since this becomes more challenging as the data rates of the camera increase, this can affect camera selection.

3. Digital Data Formats and Interfaces

Which digital data format and camera interface is right for your application?

• **CameraLink** is the latest evolution in LVDS cameras. CameraLink standardizes the interface between digital cameras and frame grabbers, which simplifies the connection to standard, off-the-shelf cables. CameraLink uses a serial transfer technology and thus requires significantly fewer conductors than previous parallel signal transmissions. This greatly simplifies the cables, allowing for smaller, more flexible, and lower cost cables. CameraLink can also support multiple output cameras and enable high-speed imaging systems.

• **FireWire and USB** are relatively recent innovations in camera output formats. Each of these fairly simple interfaces is accomplished using standard cables and existing computer ports. Currently, their data transfer speeds are limited, and, therefore, these interfaces are restricted to relatively slow, single-channel cameras.

• **GigE Vision** is the first machine vision digital interface designed to use networking technologies. These days, networking is ubiquitous in that most PCs have 1, if not 2, Gigabit interfaces. This is not the case with Firewire which is typically only available in high-end multimedia computers. There has been a tremendous investment in networking technologies over the last decades outside of the machine vision market. GigE Vision directly leverages from them by using their electrical components and specifying a protocol adapted to camera control and real-time transmission of images and video. The main benefit of using Ethernet to machine vision is the opportunity to use long cables (up to 100 meters for copper) with a digital camera. This is the first time analog cameras using long shielded cables can be replaced using a standard digital interface (all other technologies such as Firewire, USB and CameraLink cannot accommodate more than 10 meters over copper). And because the images are transferred as Ethernet packets, they are protected by a checksum. This latter property ensures that if a transmission error occurs, the application can ask for retransmission of the corrupted information. The available bandwidth of Gigabit Ethernet (slightly higher than 100 MB/s) is also well suited to a majority of image processing applications. GigE Vision provides the assurance of interoperability among product coming from different vendors.

For more information on digital data formats and interfaces, please refer to part one of this article.

4. Ancillary Equipment

Once a camera has been chosen for an application, the remaining equipment can be selected. All of this equipment will be dependent on the camera and the application.

• **Optics and lighting** should be selected to comply with the requirements of the selected camera, such as the lens mount and the spectral response. Lighting and optics is a wide-ranging topic that is beyond the scope of what can be covered in this article. However, selecting the right lighting and optics for each application is absolutely critical, and often may have more of an impact on the success of the machine vision system than selecting the proper camera. No camera, no matter how well designed or selected, will perform to its maximum capabilities if either the lighting or optics are poorly matched.

• **Software** is application driven and may be dependent on the type of interface to the acquisition system. In relation to camera selection, software should be selected to provide the best control for the required features of the camera. For example, many cameras provide for exposure control via an external signal such as EXSYNC. While this is ultimately a hardware control signal, many applications require the ability to change the exposure under software control. If this interface is crude or non-existent, the user will be mired in developing this interface from scratch. The frame grabber software should provide an easy-to-use interface to these and other camera control parameters.

Beyond this, software selection becomes highly dependent on the application. The choice of a software vendor should include such selection criteria as camera/frame grabber interface, image-processing algorithms offered, data transfer and handling sophistication, robustness of the package, and ease of integration.

Nearly all applications need some method of triggering for an acquisition to take place and, therefore, the manner in which this can be accomplished is dependent on the acquisition system interface. In many applications, the system must be synchronized with an external event, such as a part-in-place sensor, to initiate acquisition. The ability of the camera and frame grabber to reliably respond to an external trigger is usually a key requirement. Additionally, notification of a failure to deliver the requested image is often just as critical. Using a frame grabber and camera that can provide this notification and event monitoring can greatly increase the resulting system reliability. The demand for improved reliability has resulted in the development of various innovations in the industry to control, monitor and correct the image acquisition process from the time that an external trigger event occurs to the moment the data is sent to the host, providing traceability when errors do occur and permitting recovery from those errors.

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Line scan cameras often operate in concert with a shaft encoder and therefore require a frame grabber that can properly interface to common shaft encoder signals. The ability to fire a strobe and properly align this signal with the trigger signal can also be important.

• **Cabling**—CameraLink standardizes the cabling required to interface to a digital camera. In addition to the convenience and economy of being able to obtain cables from several sources, CameraLink cables also have many fewer conductors than required for older parallel signal standards.

Whether using CameraLink, LVDS, RS-422, or TTL digital cameras, the cables selected should be of high quality and adhere to the specifications for the standard. For example, using a cable that exceeds the recommended length can result in data loss or noise sensitivity, or may have unexpected consequences such as variable results from camera to camera or frame grabber to frame grabber.

One advantage of Gigabit Ethernet technology is its ability to transmit data over standard CAT-5e and CAT-6 cables to distances of up to 100m allowing for a greater distance between the camera and inspection system.

• **Recently,** Bayer mosaic filters have been integrated into sensors to provide color output. Bayer color cameras are typically available at a much lower cost than a three-chip RGB sensor. While this article will not cover the advantages and drawbacks of Bayer arrays, it is worth noting that, if a Bayer output camera is selected, a conversion will be required in order to view the color image. If a Bayer pattern camera is used, be sure that the frame grabber or software can perform the required conversions at the required rates.

Summary

In order of importance, the following steps should be taken when selecting a camera for an imaging application. Of course, other factors may precede camera selection for some imaging applications; for example, a camera must be selected to fit into an existing mounting system, or to connect to an existing interface.

1) Define the minimum object feature size.
2) Determine the minimum camera sensor resolution.
3) Select the appropriate available camera resolution.
4) Consider object movement and determine the appropriate camera sensor structure.
5) Determine the necessary camera spectral response.
6) Determine the necessary bit depth.
7) Consider what additional camera features may be necessary.
8) Determine the interface required for the acquisition system.
9) Select acquisition device and interface to camera.
10) Select the additional ancillary equipment dependant on the camera features and type of interface.

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