LEARNING – UNDERSTANDING – INTRODUCING – APPLYING

7 Big Ideas To Understanding Imaging Systems

APPLICATION NOTES

Edmund optics | worldwide

BASICS OF DIGITAL CAMERA SETTINGS FOR IMPROVED IMAGING RESULTS

Digital cameras, compared to their analog counterparts, offer greater flexibility in allowing the user to adjust camera settings through acquisition software. In some cases, the settings in analog cameras can be adjusted through hardware such as dual in-line package (DIP) switches or RS-232 connections. Nevertheless, the flexibility of modifying settings through the software greatly adds to increased image quality, speed, and contrast - factors that could mean the difference between observing a defect and missing it altogether. Many digital cameras have on board field-programmable gate arrays (FPGAs) for digital signal processing and camera functions. FPGAs perform the calculations behind many digital camera functions, as well as additional ones such as color interpolation for mosaic filters and simple image processing (in the case of smart cameras). Camera firmware encompasses the FPGA and on board memory; firmware updates are occasionally available for cameras, adding and improving features. The on board memory in digital cameras allows for storage of settings, look up tables, buffering for high transfer rates, and multi-camera networking with ethernet switches. Some of the most common digital camera settings are gain, gamma, area of interest, binning/subsampling, pixel clock, offset, and triggering. Understanding these basic settings will help to achieve the best results for a range of applications.

GAIN

Gain is a digital camera setting that controls the amplification of the signal from the camera sensor. It should be noted that this amplifies the whole signal, including any associated background noise. Most cameras have automatic gain, or autogain, which is abbreviated as AGC. Some allow the user to turn it off or set it manually.

Gain can be before or after the analog-to-digital converter (ADC). However, it is important to note that gain after the ADC is not true gain, but rather digital gain. Digital gain uses a look up table to map the digital values to other values, losing some information in the process.

Gain before the ADC can be useful for taking full advantage of the bit-depth of the camera in low light conditions, although it is almost always the case that careful lighting is more desirable. Gain can also be used to ensure that the taps of multi-tap sensors are well matched. In general, gain should be used only after optimizing the exposure setting, and then only after exposure time is set to its maximum for a given frame rate. To visually see the improvement gain can make in an image, compare Figures 1a, 1b, 2a, and 2b.

GAIN (CONT.)

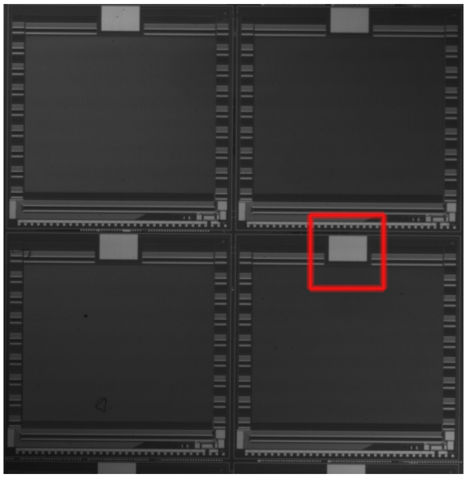

Figure 1a: Real-World Image without Gain (AGC = 0), Gamma = 1, 8MHz Pixel Clock, and 0.2ms Exposure

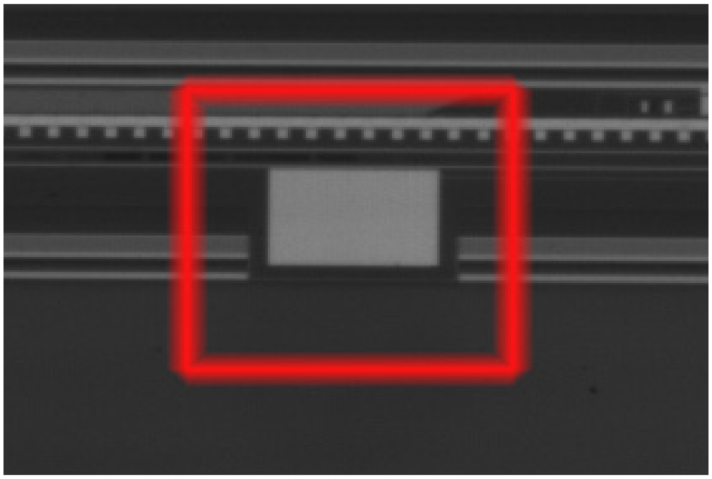

Figure 1b: Close-Up of Image with AGC = 0, Gamma = 1, 8Hz Pixel Clock, and 0.2ms Exposure

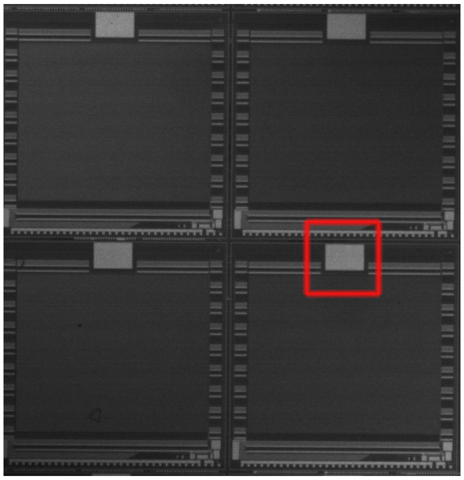

Figure 2a: Real-World Image with High Gain (AGC = 100), Gamma = 1, 8MHz Pixel Clock, and 3.4ms Exposure

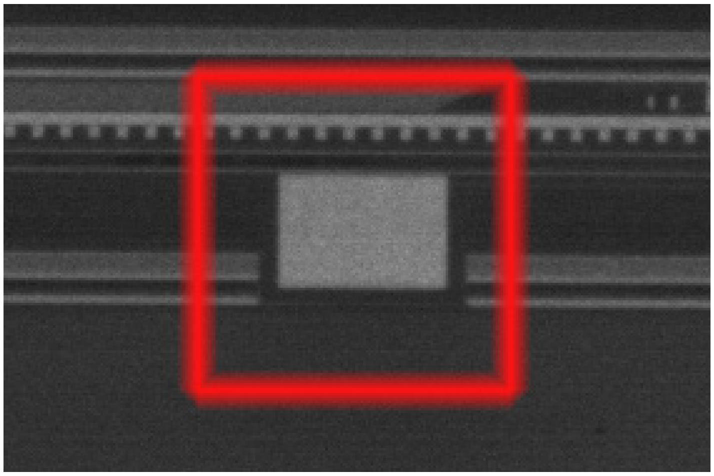

Figure 2b: Close-Up of Image with AGC = 100, Gamma = 1, 8MHz Pixel Clock, and 3.4ms Exposure

GAMMA

Gamma is a digital camera setting that controls the grayscale reproduced on the image. An image gamma of unity (Figures 3a - 3b) indicates that the camera sensor is precisely reproducing the object grayscale (linear response). A gamma setting much greater than unity results in a silhouetted image in black and white (Figures 4a – 4b). In Figure 4b, notice the decreased contrast compared to Figure 3b. Gamma can be thought of as the ability to stretch one side (either black or white) of the dynamic range of the pixel. This control is often used in signal processing to raise the signal-to-noise ratio (SNR).

Continue

GAMMA (CONT.)

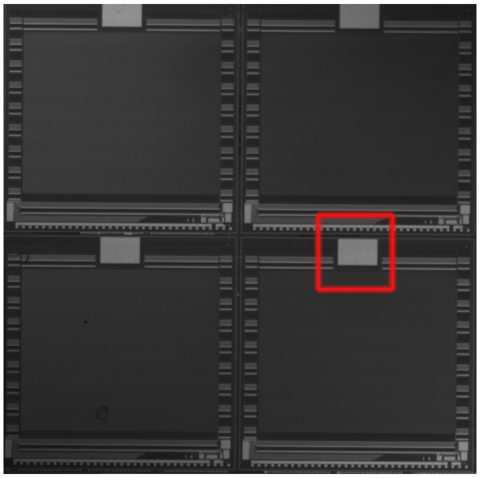

Figure 3a: Real-World Image with Gamma Equal to Unity (Gamma = 1), 10MHz Pixel Clock, and 5ms Exposure

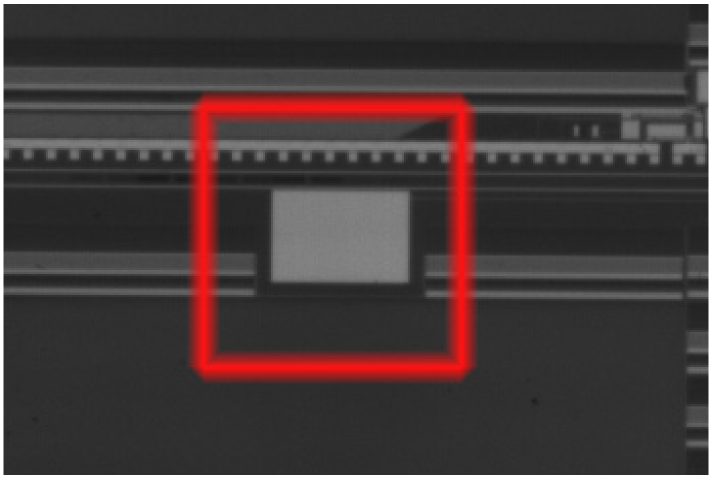

Figure 3b: Close-Up of Image with Gamma = 1, 10MHz Pixel Clock, and 5ms Exposure

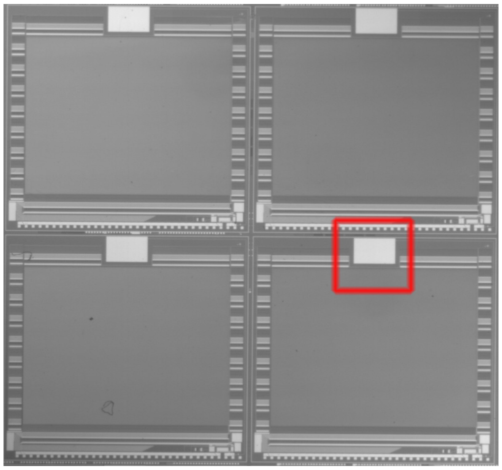

Figure 4a: Real-World Image with Gamma Greater than Unity (Gamma = 2), 10MHz Pixel Clock, and 5ms Exposure

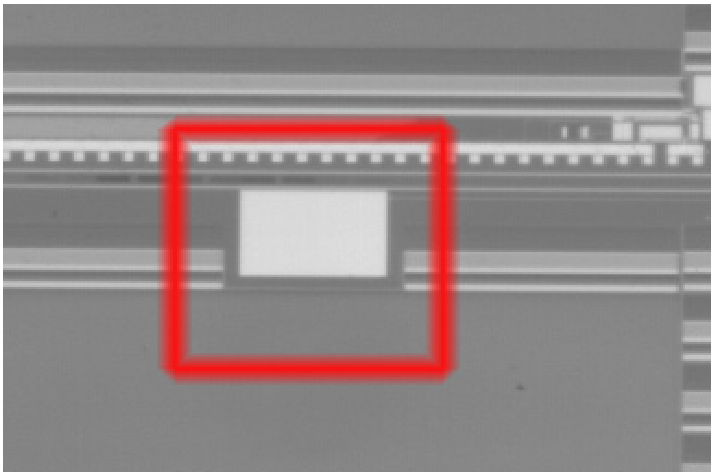

Figure 4b: Close-Up of Image with Gamma = 2, 10MH Pixel Clock, and 5ms Exposure

AREA OF INTEREST

Area of interest is a digital camera setting, either through software or on board, that allows for a subset of the camera sensor array to be read out for each field. This is useful for reducing the field of view (FOV) or resolution to the lowest required rate in order to decrease the amount of data transferred, thereby increasing the possible frame rate. The full resolution, in terms of Nyquist frequency or spatial sampling frequency, can be retained for this subset of the overall field. For example, a square field of 494 x 494 may contain all of the useful information for a given frame and can be used so as to not waste bandwidth.

BINNING/SUBSAMPLING

With binning or subsampling, the entire FOV is desired, but the full camera resolution may not be required. In this case, the gray value of adjacent pixels can be averaged together to form larger effective pixels, or only every other pixel read out. Binning or subsampling increases speed by decreasing the amount of data transferred.

Binning is specific to CCD sensors, where the charge from adjacent pixels are physically added together, increasing the effective exposure and sensitivity. Subsampling generally refers to CMOS sensors, where binning is not strictly possible; subsampling offers no increase in exposure or sensitivity. Subsampling can also be used with CCD sensors in lieu of binning when low resolution and high transfer rates are desired without the desire for the original exposure.

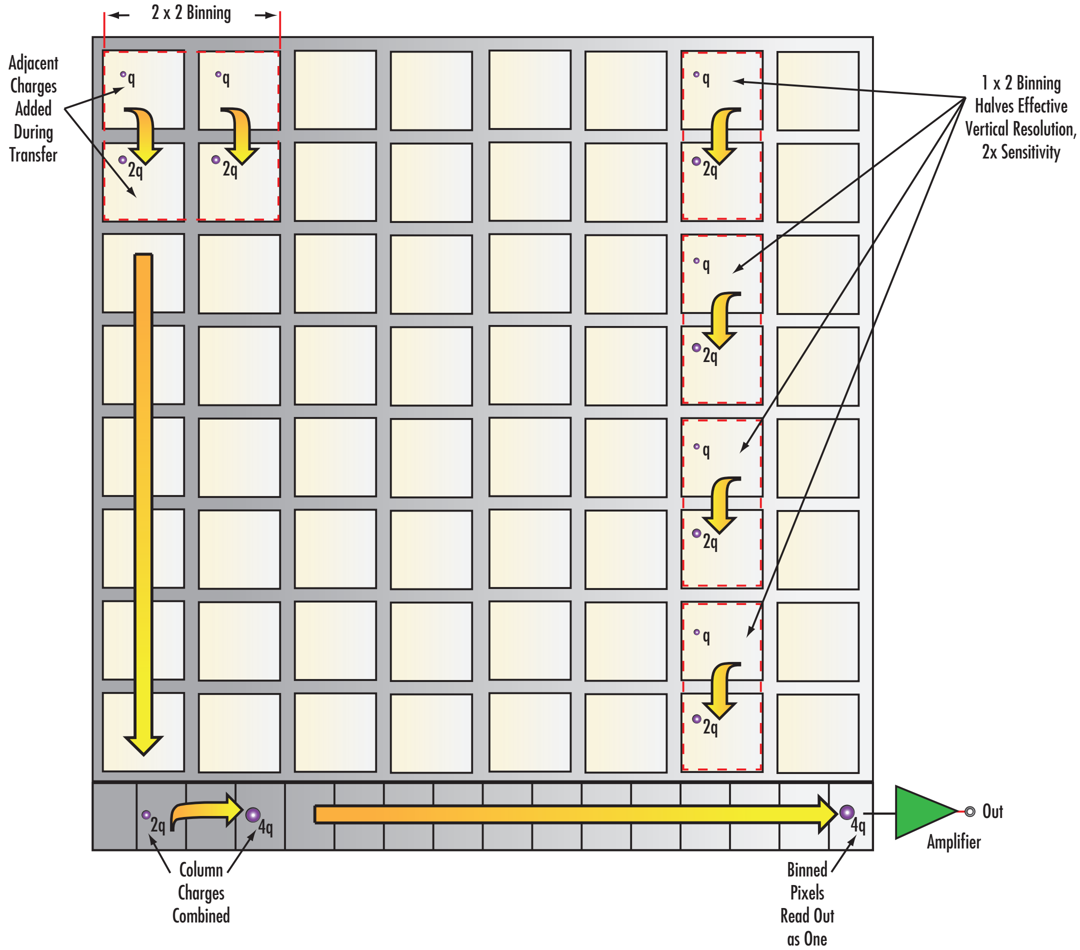

Figure 8: Traditional Filter (Left) and Hard-Sputtered Filter (Right)

PIXEL CLOCK

In a CCD camera sensor, the pixel clock describes the speed of the complementary signals which are used to move the charge packets through the shift registers towards the read out amplifiers. This determines how long it takes to read out the entire sensor, but it is also limited by noise and spillover issues which occur when the packets are transferred too quickly. For example, two cameras with identical sensors may use different pixel clock rates, leading to different performances in saturation capacity (linear range) and frame rate. This setting is not readily user adjustable, as it is generally set to an optimal value specific to the sensor and FPGA capabilities. Overclocking a sensor by increasing the pixel clock can also lead to thermal issues.

Continue

OFFSET

Offset refers to the DC component of a video or image signal, and effectively sets the black level of the image. The black level is the pixel level (in electrons, or volts) which corresponds to a pixel value of zero. This is often used with a histogram to ensure the full use of the camera bit-depth, effectively raising signal-to-noise. Pushing non-black pixels to zero lightens the image, although it gives no improvement in the data. By increasing the black level, offset is used as a simple machine vision image processing technique for brightening and effectively creating a threshold (setting all pixels below a certain value to zero to highlight features) for blob detection.

TRIGGERING

Depending upon the application, it can be useful to expose or activate pixels only when an event of interest occurs. In this case, the user can use the digital camera setting of trigger to make the camera acquire images only when a command is given. This can be used to synchronize image capture with a strobed light source, or take an image when an object passes a certain point or activates a proximity switch, the latter being useful in situations where images are being stored for review at a later time. Trigger can also be used in occasions when a user needs to take a sequence of images in a non-periodic fashion, such as with a constant frame rate.

Triggering can be done through hardware or software. Hardware triggers are ideal for high precision applications, where the latency intrinsic to a software trigger is unacceptable (which can be many milliseconds). Software triggers are often easier to implement because they take the form of a computer command sent through the normal communication path. An example of a software trigger is the snap function in image viewing software.

Though a host of additional digital camera settings exist, it is important to understand the basics of gain, gamma, area of interest, binning/subsampling, pixel clock, offset, and trigger. These functions lay the groundwork for advanced image processing techniques that require knowledge of the aforementioned basic settings.

CAMERA RESOLUTION FOR IMPROVED IMAGING SYSTEM PERFORMANCE

Camera resolution and contrast play an integral role in both the optics and electronics of an imaging system. Though camera resolution and contrast may seem like optical parameters, pixel count and size, TV lines, camera MTF, Nyquist limit, pixel depth/grayscale, dynamic range, and SNR contribute to the quality of what a user is trying to image. With tech tips for each important parameter, imaging users from novice to expert can learn about camera resolution as it pertains to the imaging electronics of a system.

PIXEL COUNT AND PIXEL SIZE

To understand a camera's pixel count and pixel size, consider the AVT Stingray F-145 Firewire camera series. Each F-145 contains a Sony ICX285 sensor of 1392 x 1040 (horizontal x vertical) pixels on a 9.0mm x 6.7mm sensor. If one imagines the field of view as a rectangle divided into 1392 x 1040 squares (Figure 1), then the minimum resolvable detail is equal to two of these squares, or pixels (Figure 2). *Tech Tip #1 is: The more pixels within a field of view (FOV), the better the resolution.* However, a large number of pixels requires either a larger sensor or smaller-sized individual pixels. *This leads to Tech Tip #2: Using a larger sensor to achieve more pixels means the imaging lens magnification and/or or field of view will change.* Conversely, if smaller pixels are used, the imaging lens may not be able to hold the resolution of the system due to the finite spatial frequency response of optics, primarily caused by design issues or the diffraction limit of the aperture.

The number of pixels also affects the frame rate of the camera. For example, each pixel has 8-bits of information that must be transferred in the reconstruction of the image. *Tech Tip #3: The more pixels on a sensor, the higher the camera resolution but lower the frame rate.* If both high frame rates and high resolution (e.g. many pixels) are required, then the system price and set up complexity quickly increases, often at a rate not necessarily proportional to the number of pixels.

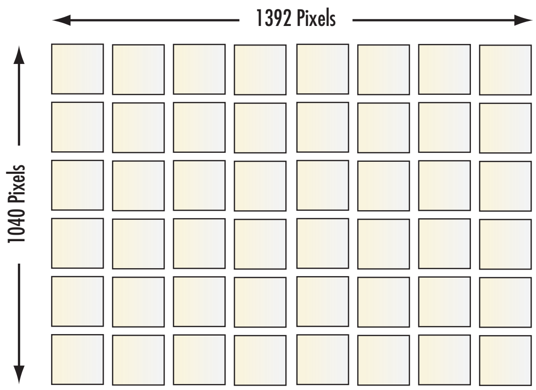

Figure 1: Illustration of Pixels on a Camera Sensor

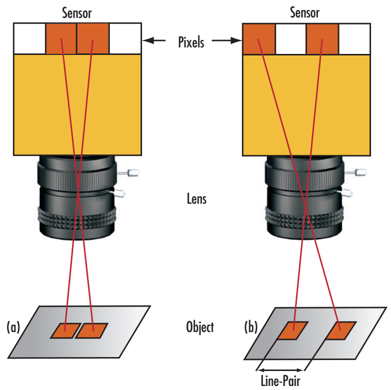

Figure 2: Pair of Pixels Unresolved (a) vs. Resolved (b)

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TV LINES

In analog CCD cameras, the TV Line (TVL) specification is often used to evaluate resolution. The TVL specification is a unit of resolution based on a bar target with equally spaced lines. If the target is extended so that it covers the FOV, the TVL number is calculated by summing all of the resulting lines and spaces. Equations 1 and 2 provide simple calculations for determining horizontal (H) and vertical (V) TVL. Included in Equation 1 is a normalization factor necessary to account for a sensor's 4:3 aspect ratio. Figure 3 shows an IEEE approved testing target for measuring TVLs of a system.

(1)

$$H\ TVL = \frac{2\ [H\ Resolution\ (lines/mm)]\ [H\ Sensing\ Distance\ (mm)]}{1.333}$$

(2)

$$V\ TVL = 2\ [V\ Resolution\ (lines/mm)]\ [V\ Sensing\ Distance\ (mm)]$$

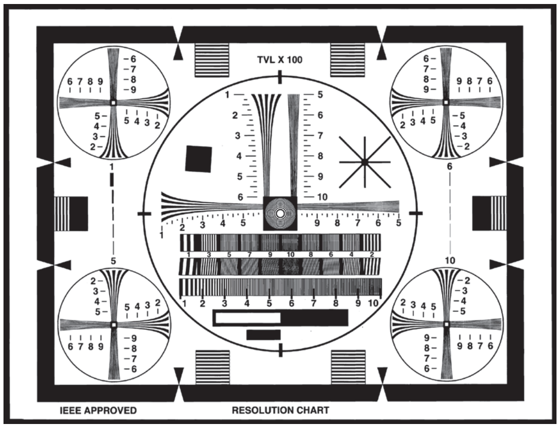

Figure 3: IEEE Approved Target for Measuring TV Lines (TVLs)

MODULATION TRANSFER FUNCTION (MTF)

The most effective means of specifying the resolution of a camera is its modulation transfer function (MTF). The MTF is a way of incorporating contrast and resolution to determine the total performance of a sensor. A useful property of the MTF is the multiplicative property of transfer functions; the MTF of each component (imaging lens, camera sensor, display, etc.) can be multiplied to get the overall system response (Figure 4).

The MTF takes into account not only the spatial resolution of the number of pixels/mm, but also the roll off that occurs at high spatial frequencies due to pixel cross talk and finite fill factors. *Tech Tip #4: It is not the case that a sensor will offer 100% contrast at a spatial frequency equal to the inverse of its pixel size.*

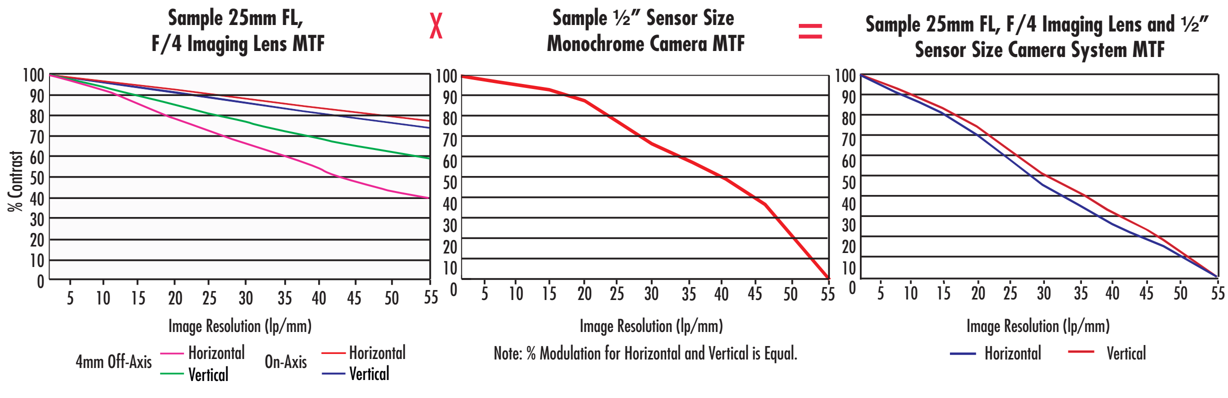

Figure 4: System MTF is the Product of the MTF of Each Individual Component

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NYQUIST LIMIT

The absolute limiting resolution of a sensor is determined by its Nyquist limit. This is defined as being one half of the sampling frequency, a.k.a the number of pixels/mm (Equation 3). For example, the Sony ICX285 is a monochrome CCD sensor with a horizontal active area of 9mm containing 1392 horizontal pixels each 6.45μm in size. This represents a horizontal sampling frequency of 155 pixels/mm (1392 pixels / 9mm = 1mm / 0.00645 mm/pixel = 155). The Nyquist limit of this calculates to 77.5 lp/mm. Keep in mind that image processing methods exist, such as sub-pixel sampling, which enable a user to statistically extrapolate higher resolution than the Nyquist limit in the special case of edges and other geometrically simple figures. At the Nyquist limit, contrast is phase dependent for a constant incident square wave (imagine one pixel on, one pixel off, or each pixel with half a cycle). It is, therefore, common to include the Kell factor (~0.7), which reflects the deviation of the actual frequency response from the Nyquist frequency. Most importantly, the Kell factor compensates for the space between pixels. *Tech Tip #5: Sampling at spatial frequencies above the system's Nyquist limit can create spurious signals and aliasing effects that are undesirable and unavoidable.*

(3)

$$\text{Nyquist Limit (lp/mm)} = \frac{1}{2}\,[\text{Kell Factor}]\,[\text{Sampling Frequency (pixels/mm)}]$$

PIXEL DEPTH/GRAYSCALE

Often referred to as grayscale or, (less precisely) the dynamic range of a CCD camera, pixel depth represents the number of steps of gray in the image. Pixel depth is closely related to the minimum amount of contrast detectable by a sensor. In analog cameras, the signal is a time varying voltage proportional to the intensity of the light incident on the sensor, specified below the saturation point. After digitizing, this continuous voltage is effectively divided into discrete levels, each of which corresponds to a numerical value. At unity gain, light that has 100% saturation of the pixel will be given a value of 2N-1, where N is the number of bits, and the absence of light is given a value of 0. *Tech Tip #6: The more bits in a camera, the smoother the digitization process*. Also, more bits means higher accuracy and more information. With enough bits, the human eye can no longer determine the difference between a continuous grayscale and its digital representation. The number of bits used in digitization is called the bit depth or pixel depth.

For an example of pixel depth, consider the Sony XC series of cameras, which offer 256 shades of gray, and the Edmund Optics USB 2.0 CMOS series of cameras, which are available in 8-bit (256 grayscale) and 10-bit (1024 grayscales) models. Generally, 12-bit and 14-bit cameras have the option of running in a lower pixel depth mode. Although pixel depths above 8-bits are useful for signal processing, computer displays only offer 8-bit resolution. Thus, if the images from the camera will be viewed only on a monitor, the additional data does nothing but reduce frame rate. Figure 5 illustrates different pixel depths. Notice the smooth progression from gray to white as bit depth increases.

Figure 5: Illustration of 2-Bit (Top), 4-Bit (Middle), and 8-Bit (Bottom) Grayscales

Continue

DYNAMIC RANGE

Dynamic range is the difference between the lowest detectable light level and the highest detectable light level. Physically, this is determined by the saturation capacity of each pixel, the dark current or dark noise, the ADC circuits, and gain settings. *Tech Tip #7: For high dynamic ranges, more bits are required to describe the grayscale in a meaningful fashion.* However, it is important to note that, with consideration of the signal-to-noise-ratio, using 14 bits to describe a 50dB dynamic range gives redundant bits and no additional information.

SIGNAL-TO-NOISE RATIO (SNR)

The signal-to-noise ratio (SNR) is closely linked to the dynamic range of a camera. Tech Tip #8: A higher SNR yields a higher possible number of steps in the grayscale (higher contrast) produced by a camera. The SNR is expressed in terms of decibels (dB) in analog systems and bits in digital systems. In general, 6dB of analog SNR converts to 1-bit when digitized. For digital or analog cameras, X bits (or the equivalent in analog systems) correspond to 2^X grayscales (i.e. 8-bit cameras have 2^8 or 256 gray levels).

There are two primary sources for the noise in camera sensors. The first is imperfections in the chip, which result in non-uniform dark current and crosstalk. The second is thermal noise and other electronic variations. Chip imperfections and electronic variations reduce camera resolution and should be monitored to determine how to best compensate for them within the imaging system.

The basics of camera resolution can be divided into parameters of pixel count and size, TV lines, camera MTF, Nyquist limit, pixel depth/grayscale, dynamic range, and SNR. Understanding these basic terms allows a user to move from being a novice to an imaging expert.

UNDERSTANDING CAMERA SENSORS FOR MACHINE VISION APPLICATIONS

Imaging electronics, in addition to imaging optics, play a significant role in the performance of an imaging system. Proper integration of all components, including camera, capture board, software, and cables results in optimal system performance. Before delving into any additional topics, it is important to understand the camera sensor and key concepts and terminology associated with it.

The heart of any camera is the sensor; modern sensors are solid-state electronic devices containing up to millions of discrete photodetector sites called pixels. Although there are many camera manufacturers, the majority of sensors are produced by only a handful of companies. Still, two cameras with the same sensor can have very different performance and properties due to the design of the interface electronics. In the past, cameras used phototubes such as Vidicons and Plumbicons as image sensors. Though they are no longer used, their mark on nomenclature associated with sensor size and format remains to this day. Today, almost all sensors in machine vision fall into one of two categories: Charge-Coupled Device (CCD) and Complementary Metal Oxide Semiconductor (CMOS) imagers.

SENSOR CONSTRUCTION

CHARGE-COUPLED DEVICE (CCD)

The charge-coupled device (CCD) was invented in 1969 by scientists at Bell Labs in New Jersey, USA. For years, it was the prevalent technology for capturing images, from digital astrophotography to machine vision inspection. The CCD sensor is a silicon chip that contains an array of photosensitive sites (Figure 1). The term charge-coupled device actually refers to the method by which charge packets are moved around on the chip from the photosites to readout, a shift register, akin to the notion of a bucket brigade. Clock pulses create potential wells to move charge packets around on the chip, before being converted to a voltage by a capacitor. The CCD sensor is itself an analog device, but the output is immediately converted to a digital signal by means of an analog-to-digital converter (ADC) in digital cameras, either on or off chip. In analog cameras, the voltage from each site is read out in a particular sequence, with synchronization pulses added at some point in the signal chain for reconstruction of the image.

The charge packets are limited to the speed at which they can be transferred, so the charge transfer is responsible for the main CCD drawback of speed, but also leads to the high sensitivity and pixel-to-pixel consistency of the CCD. Since each charge packet sees the same voltage conversion, the CCD is very uniform across its photosensitive sites. The charge transfer also leads to the phenomenon of blooming, wherein charge from one photosensitive site spills over to neighboring sites due to a finite well depth or charge capacity, placing an upper limit on the useful dynamic range of the sensor. This phenomenon manifests itself as the smearing out of bright spots in images from CCD cameras.

Continue

CHARGE-COUPLED DEVICE (CCD) (CONT.)

To compensate for the low well depth in the CCD, microlenses are used to increase the fill factor, or effective photosensitive area, to compensate for the space on the chip taken up by the charge-coupled shift registers. This improves the efficiency of the pixels, but increases the angular sensitivity for incoming light rays, requiring that they hit the sensor near normal incidence for efficient collection.

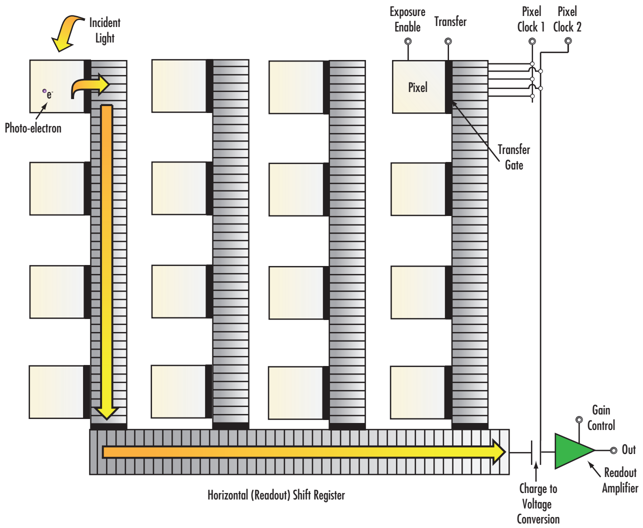

Figure 1: Block Diagram of a Charge-Coupled Device (CCD)

COMPLEMENTARY METAL OXIDE SEMICONDUCTOR (CMOS)

The complementary metal oxide semiconductor (CMOS) was invented in 1963 by Frank Wanlass. However, he did not receive a patent for it until 1967, and it did not become widely used for imaging applications until the 1990s. In a CMOS sensor, the charge from the photosensitive pixel is converted to a voltage at the pixel site and the signal is multiplexed by row and column to multiple on chip digital-to-analog converters (DACs). Inherent to its design, CMOS is a digital device. Each site is essentially a photodiode and three transistors, performing the functions of resetting or activating the pixel, amplification and charge conversion, and selection or multiplexing (Figure 2). This leads to the high speed of CMOS sensors, but also low sensitivity as well as high fixed-pattern noise due to fabrication inconsistencies in the multiple charge to voltage conversion circuits.

The multiplexing configuration of a CMOS sensor is often coupled with an electronic rolling shutter; although, with additional transistors at the pixel site, a global shutter can be accomplished wherein all pixels are exposed simultaneously and then readout sequentially. An additional advantage of a CMOS sensor is its low power consumption and dissipation compared to an equivalent CCD sensor, due to less flow of charge, or current. Also, the CMOS sensor's ability to handle high light levels without blooming allows for its use in special high dynamic range cameras, even capable of imaging welding seams or light filaments. CMOS cameras also tend to be smaller than their digital CCD counterparts, as digital CCD cameras require additional off-chip ADC circuitry.

The multilayer MOS fabrication process of a CMOS sensor does not allow for the use of microlenses on the chip, thereby decreasing the effective collection efficiency or fill factor of the sensor in comparison with a CCD equivalent. This low efficiency combined with pixel-to-pixel inconsistency contributes to a lower signal-to-noise ratio and lower overall image quality than CCD sensors. Refer to Table 1 for a general comparison of CCD and CMOS sensors.

COMPLEMENTARY METAL OXIDE SEMICONDUCTOR (CMOS) (CONT.)

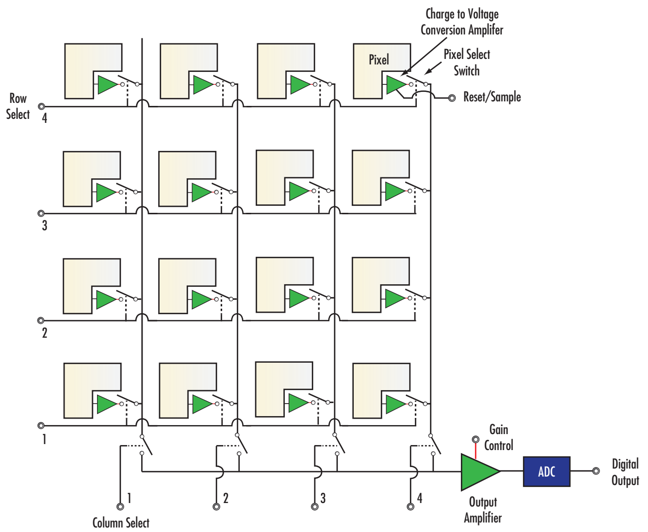

Figure 2: Block Diagram of a Complementary Metal Oxide Semiconductor (CMOS)

Table 1: Comparison of (CCD) and (CMOS) Sensors

Sensor	**CCD**	**CMOS**
Pixel Signal	*Electron Packet*	*Voltage*
Chip Signal	*Analog*	*Digital*
Fill Factor	*High*	*Moderate*
Responsivity	*Moderate*	*Moderate - High*
Noise Level	*Low*	*Moderate - High*
Dynamic Range	*High*	*Moderate*
Uniformity	*High*	*Low*
Resolution	*Low - High*	*Low - High*
Speed	*Moderate - High*	*High*
Power Consumption	*Moderate - High*	*Low*
Complexity	*Low*	*Moderate*
Cost	*Moderate*	*Moderate*

ALTERNATIVE SENSOR MATERIALS

Short-wave infrared (SWIR) is an emerging technology in imaging. It is typically defined as light in the 0.9 – 1.7μm wavelength range, but can also be classified from 0.7 – 2.5μm. Using SWIR wavelengths allows for the imaging of density variations, as well as through obstructions such as fog. However, a normal CCD and CMOS image is not sensitive enough in the infrared to be useful. As such, special indium gallium arsenide (InGaAs) sensors are used. The InGaAs material has a band gap, or energy gap, that makes it useful for generating a photocurrent from infrared energy. These sensors use an array of InGaAs photodiodes, generally in the CMOS sensor architecture.

At even longer wavelengths than SWIR, thermal imaging becomes dominant. For this, a microbolometer array is used for its sensitivity in the 7 - 14μm wavelength range. In a microbolometer array, each pixel has a bolometer which has a resistance that changes with temperature. This resistance change is read out by conversion to a voltage by electronics in the substrate (Figure 3). These sensors do not require active cooling, unlike many infrared imagers, making them quite useful.

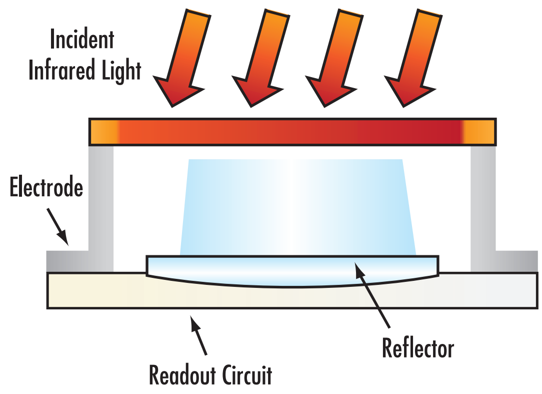

Figure 3: Illustration of Cross-Section of Microbolometer Sensor Array

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SENSOR FEATURES

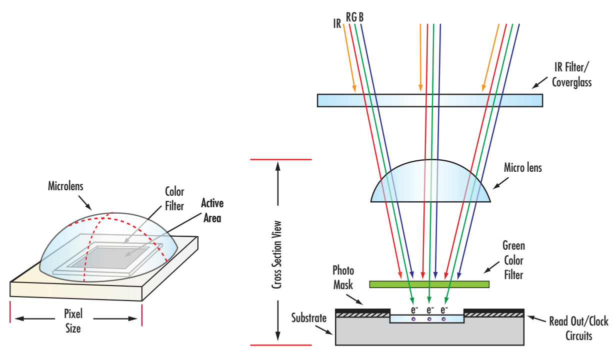
PIXELS

When light from an image falls on a camera sensor, it is collected by a matrix of small potential wells called pixels. The image is divided into these small discrete pixels. The information from these photosites is collected, organized, and transferred to a monitor to be displayed. The pixels may be photodiodes or photocapacitors, for example, which generate a charge proportional to the amount of light incident on that discrete place of the sensor, spatially restricting and storing it. The ability of a pixel to convert an incident photon to charge is specified by its quantum efficiency. For example, if for ten incident photons, four photo-electrons are produced, then the quantum efficiency is 40%. Typical values of quantum efficiency for solid-state imagers are in the range of 30 - 60%. The quantum efficiency depends on wavelength and is not necessarily uniform over the response to light intensity. Spectral response curves often specify the quantum efficiency as a function of wavelength.

In digital cameras, pixels are typically square. Common pixel sizes are between 3 - 10μm. Although sensors are often specified simply by the number of pixels, the size is very important to imaging optics. Large pixels have, in general, high charge saturation capacities and high signal-to-noise ratios (SNRs). With small pixels, it becomes fairly easy to achieve high resolution for a fixed sensor size and magnification, although issues such as blooming become more severe and pixel crosstalk lowers the contrast at high spatial frequencies. A simple measure of sensor resolution is the number of pixels per millimeter.

Analog CCD cameras have rectangular pixels (larger in the vertical dimension). This is a result of a limited number of scanning lines in the signal standards (525 lines for NTSC, 625 lines for PAL) due to bandwidth limitations. Asymmetrical pixels yield higher horizontal resolution than vertical. Analog CCD cameras (with the same signal standard) usually have the same vertical resolution. For this reason, the imaging industry standard is to specify resolution in terms of horizontal resolution.

Figure 4: Illustration of Camera Sensor Pixels with RGB Color and Infrared Blocking Filters



SENSOR SIZE

The size of a camera sensor's active area is important in determining the system's field of view (FOV). Given a fixed primary magnification (determined by the imaging lens), larger sensors yield greater FOVs. There are several standard area-scan sensor sizes: 1/4", 1/3", 1/2", 1/1.8", 2/3", 1" and 1.2", with larger available (Figure 5). The nomenclature of these standards dates back to the Vidicon vacuum tubes used for television broadcast imagers, so it is important to note that the actual dimensions of the sensors differ.

Note: There is no direct connection between the sensor size and its dimensions; it is purely a legacy convention. However, most of these standards maintain a 4:3 (Horizontal: Vertical) dimensional aspect ratio.

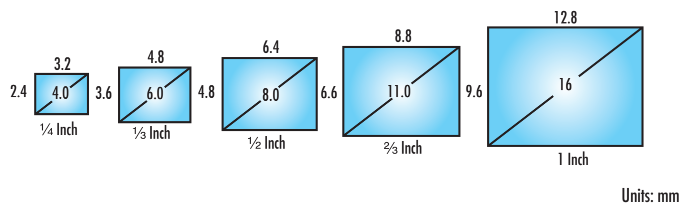


Figure 5: Illustration of Sensor Size Dimensions for Standard Camera Sensors

Continue

SENSOR SIZE (CONT.)

One issue that often arises in imaging applications is the ability of an imaging lens to support certain sensor sizes. If the sensor is too large for the lens design, the resulting image may appear to fade away and degrade towards the edges because of vignetting (extinction of rays which pass through the outer edges of the imaging lens). This is commonly referred to as the tunnel effect, since the edges of the field become dark. Smaller sensor sizes do not yield this vignetting issue.

FRAME RATE AND SHUTTER SPEED

The frame rate refers to the number of full frames (which may consist of two fields) composed in a second. For example, an analog camera with a frame rate of 30 frames/second contains two 1/60 second fields. In high-speed applications, it is beneficial to choose a faster frame rate to acquire more images of the object as it moves through the FOV.

The shutter speed corresponds to the exposure time of the sensor. The exposure time controls the amount of incident light. Camera blooming (caused by over-exposure) can be controlled by decreasing illumination, or by increasing the shutter speed. Increasing the shutter speed can help in creating snap shots of a dynamic object which may only be sampled 30 times per second (live video).

Unlike analog cameras where, in most cases, the frame rate is dictated by the display, digital cameras allow for adjustable frame rates. The maximum frame rate for a system depends on the sensor readout speed, the data transfer rate of the interface including cabling, and the number of pixels (amount of data transferred per frame). In some cases, a camera may be run at a higher frame rate by reducing the resolution by binning pixels together or restricting the area of interest. This reduces the amount of data per frame, allowing for more frames to be transferred for a fixed transfer rate. To a good approximation, the exposure time is the inverse of the frame rate. However, there is a finite minimum time between exposures (on the order of hundreds of microseconds) due to the process of resetting pixels and reading out, although many cameras have the ability to readout a frame while exposing the next time (pipelining); this minimum time can often be found on the camera datasheet.

CMOS cameras have the potential for higher frame rates, as the process of reading out each pixel can be done more quickly than with the charge transfer in a CCD sensor's shift register. For digital cameras, exposures can be made from tens of seconds to minutes, although the longest exposures are only possible with CCD cameras, which have lower dark currents and noise compared to CMOS. The noise intrinsic to CMOS imagers restricts their useful exposure to only seconds.

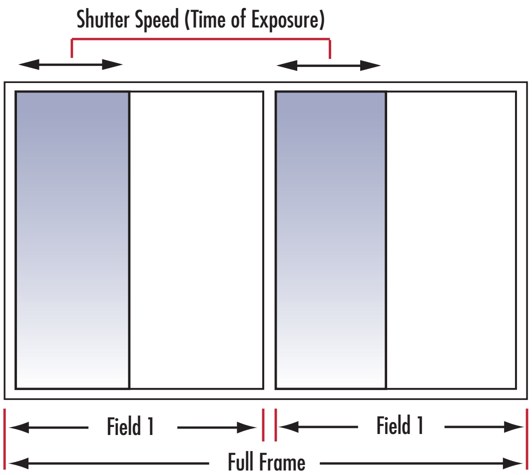


Figure 6: Relationship between Shutter Speed, Fields, and Full Frame for Interlaced Display

Continue

ELECTRONIC SHUTTER

Until a few years ago, CCD cameras used electronic or global shutters, and all CMOS cameras were restricted to rolling shutters. A global shutter is analogous to a mechanical shutter, in that all pixels are exposed and sampled simultaneously, with the readout then occurring sequentially; the photon acquisition starts and stops at the same time for all pixels. On the other hand, a rolling shutter exposes, samples, and reads out sequentially; it implies that each line of the image is sampled at a slightly different time. Intuitively, images of moving objects are distorted by a rolling shutter; this effect can be minimized with a triggered strobe placed at the point in time where the integration period of the lines overlaps. Note that this is not an issue at low speeds. Implementing global shutter for CMOS requires a more complicated architecture than the standard rolling shutter model, with an additional transistor and storage capacitor, which also allows for pipelining, or beginning exposure of the next frame during the readout of the previous frame. Since the availability of CMOS sensors with global shutters is steadily growing, both CCD and CMOS cameras are useful in high-speed motion applications.

In contrast to global and rolling shutters, an asynchronous shutter refers to the triggered exposure of the pixels. That is, the camera is ready to acquire an image, but it does not enable the pixels until after receiving an external triggering signal. This is opposed to a normal constant frame rate, which can be thought of as internal triggering of the shutter.

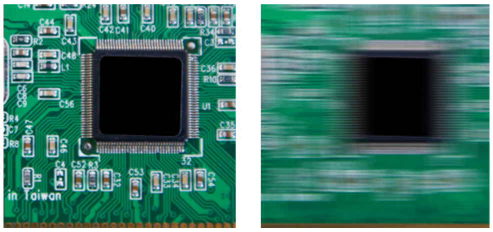


Figure 7a: Comparison of Motion Blur. Sensor Chip on a Fast-Moving Conveyer with Triggered Global Shutter (Left) and Continuous Global Shutter (Right)

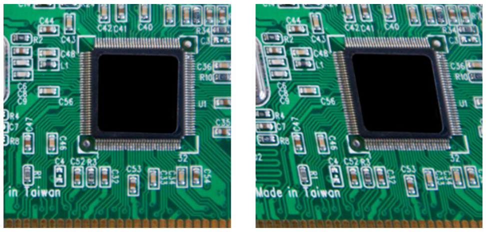


Figure 7b: Comparison of Motion Blur in Global and Rolling Shutters. Sensor Chip on a Slow-Moving Conveyer with Global Shutter (Left) and Rolling Shutter (Right)

SENSOR TAPS

One way to increase the readout speed of a camera sensor is to use multiple taps on the sensor. This means that instead of all pixels being read out sequentially through a single output amplifier and ADC, the field is split and read to multiple outputs. This is commonly seen as a dual tap where the left and right halves of the field are readout separately. This effectively doubles the frame rate, and allows the image to be reconstructed easily by software. It is important to note that if the gain is not the same between the sensor taps, or if the ADCs have slightly different performance, as is usually the case, then a division occurs in the reconstructed image. The good news is that this can be calibrated out. Many large sensors which have more than a few million pixels use multiple sensor taps. This, for the most part, only applies to progressive scan digital cameras; otherwise, there will be display difficulties. The performance of a multiple tap sensor depends largely on the implementation of the internal camera hardware.

SPECTRAL PROPERTIES

MONOCHROME CAMERAS

CCD and CMOS sensors are sensitive to wavelengths from approximately 350 - 1050nm, although the range is usually given from 400 - 1000nm. This sensitivity is indicated by the sensor's spectral response curve (Figure 8). Most high-quality cameras provide an infrared (IR) cut-off filter for imaging specifically in the visible spectrum. These filters are sometimes removable for near-IR imaging.

CMOS sensors are, in general, more sensitive to IR wavelengths than CCD sensors. This results from their increased active area depth. The penetration depth of a photon depends on its frequency, so deeper depths for a given active area thickness produces less photoelectrons and decreases quantum efficiency.

Continue

MONOCHROME CAMERAS

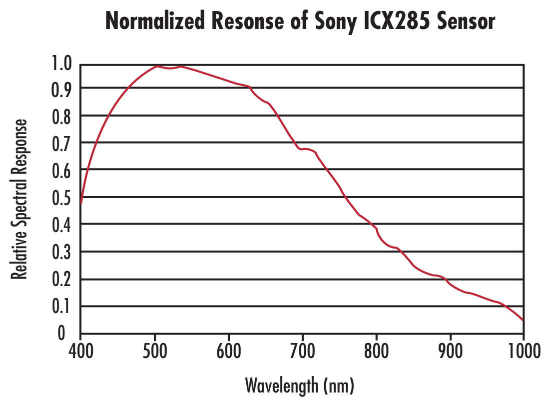


Figure 8: Normalized Spectral Response of a Typical Monochrome CCD

COLOR CAMERAS

The solid state sensor is based on a photoelectric effect and, as a result, cannot distinguish between colors. There are two types of color CCD cameras: single chip and three-chip. Single chip color CCD cameras offer a common, low-cost imaging solution and use a mosaic (e.g. Bayer) optical filter to separate incoming light into a series of colors. Each color is, then, directed to a different set of pixels (Figure 9a). The precise layout of the mosaic pattern varies between manufacturers. Since more pixels are required to recognize color, single chip color cameras inherently have lower resolution than their monochrome counterparts; the extent of this issue is dependent upon the manufacturer-specific color interpolation algorithm.

Three-chip color CCD cameras are designed to solve this resolution problem by using a prism to direct each section of the incident spectrum to a different chip (Figure 9b). More accurate color reproduction is possible, as each point in space of the object has separate RGB intensity values, rather than using an algorithm to determine the color. Three-chip cameras offer extremely high resolutions but have lower light sensitivities and can be costly. In general, special 3CCD lenses are required that are well corrected for color and compensate for the altered optical path and, in the case of C-mount, reduced clearance for the rear lens protrusion. In the end, the choice of single chip or three-chip comes down to application requirements.

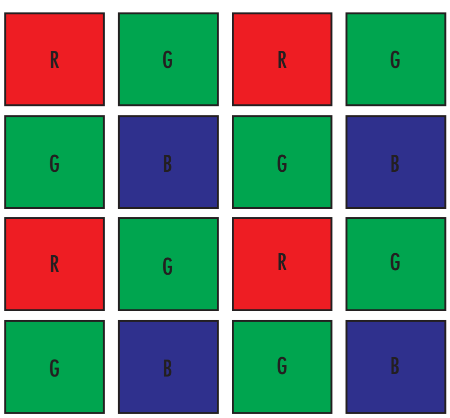


Figure 9a: Single-Chip Color CCD Camera Sensor using Mosaic Filter to Filter Colors

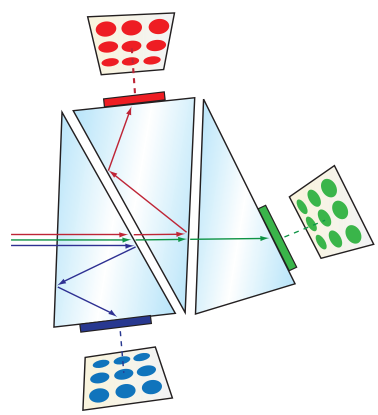


Figure 9b: Single-Chip Color CCD Camera Sensor using Mosaic Filter to Filter Colors

The most basic component of a camera system is the sensor. The type of technology and features greatly contributes to the overall image quality, therefore knowing how to interpret camera sensor specifications will ultimately lead to choosing the best imaging optics to pair with it.

CAMERA TYPES AND INTERFACES FOR MACHINE VISION APPLICATIONS

As imaging technology advances, the types of cameras and their interfaces continually evolve to meet the needs of a host of applications. For machine vision applications in the semiconductor, electronics, biotechnology, assembly, and manufacturing industries where inspection and analysis are key, using the best camera system for the task at hand is crucial to achieving the best image quality. From analog and digital cameras, to progressive scan and interlaced scan formats, to firewire and GigE interfaces, understanding parameters such as camera types, digital interfaces, power, and software provides a great opportunity to move from imaging novice to imaging expert.

CAMERA TYPES AND THEIR ADVANTAGES

ANALOG VS. DIGITAL CAMERAS

On the most general level, cameras can be divided into two types: analog and digital. Analog cameras transmit a continuously variable electronic signal in real-time. The frequency and amplitude of this signal is then interpreted by an analog output device as video information. Both the quality of the analog video signal and the way in which it is interpreted affect the resulting video images. Also, this method of data transmission has both pros and cons. Typically, analog cameras are less expensive and less complicated than their digital counterparts, making them cost-effective and simple solutions for common video applications. However, analog cameras have upper limits on both resolution (number of TV lines) and frame rate. For example, one of the most common video signal formats in the United States, called NTSC, is limited to about 800 TV lines (typically 525) and 30 frames per second. The PAL standard uses 625 TV lines and a frame rate of 25 frames per second. Analog cameras are also very susceptible to electronic noise, which depends on commonly-overlooked factors such as cable length and connector type.

Digital cameras, the newest introduction and steadily becoming the most popular, transmit binary data (a stream of ones and zeroes) in the form of an electronic signal. Although the voltage corresponding to the light intensity for a given pixel is continuous, the analog-to-digital conversion process discretizes this and assigns a grayscale value between 0 (black) and 2^{N-1}, where N is the number of bits of the encoding. An output device then converts the binary data into video information. Of importance are two key differences unique to digital and not analog cameras types:

1) The digital video signal is exactly the same when it leaves the camera as when it reaches an output device.

2T The video signal can only be interpreted in one way.

Continue

ANALOG VS. DIGITAL CAMERAS (CONT.)

These differences eliminate errors in both transmission of the signal and interpretation by an output device due to the display. Compared to analog counterparts, digital cameras typically offer higher resolution, higher frame rates, less noise, and more features. Unfortunately these advantages come with costs - digital cameras are generally more expensive than analog ones. Furthermore, feature-packed cameras may involve more complicated setup, even for video systems that require only basic capabilities. Digital cameras are also limited to shorter cable lengths in most cases. Table 1 provides a brief comparison of analog and digital cameras types.

Table 1: Comparison of Analog Camera and Digital Camera Types

Analog Cameras	Digital Cameras
Vertical resolution is limited by the bandwidth of the analog signal	*Vertical resolution is not limited; offer high resolution in both horizontal and vertical directions*
Standard-sized sensors	*With no bandwidth limit, offer large numbers of pixel and sensorrs, resulting in high resolution*
Computers and capture boards can be used for digitizing, but are not necessary for display	*Computer and capture board (in some cases) required to display signal*
Analog printing and recording easily incorperated into system	*Signal can be compressed so user can transmit in low bandwidth*
Signal is susceptible to noise and interference which causes loss in quality	*Signal can be compressed so user can transmit in low bandwidth*
Limited frame rates	*High frame rates and fast shutters*

INTERLACED VS. PROGRESSIVE SCAN CAMERAS

Camera formats can be divided into interlaced, progressive, area, and line scan. To easily compare, it is best to group them into interlaced vs. progressive and area vs. line. Conventional CCD cameras use interlaced scanning across the sensor. The sensor is divided into two fields: the odd field (rows 1, 3, 5..., etc.) and the even field (rows 2, 4, 6..., etc.). These fields are then integrated to produce a full frame. For example, with a frame rate of 30 frames per second (fps), each field takes 1/60 of a second to read. For most applications, interlaced scanning does not cause a problem. However, some trouble can develop in high-speed applications because by the time the second field is scanned, the object has already moved. This causes ghosting or blurring effects in the resulting image (Figures 1a – 1b). In Figure 1a, notice how TECHSPEC® Man appears skewed when taking his picture with an interlaced scanning sensor.

In contrast, progressive scanning solves the high-speed issue by scanning the lines sequentially (rows 1, 2, 3, 4..., etc.). Unfortunately, the output for progressive scanning has not been standardized so care should be taken when choosing hardware. Some progressive scan cameras offer an analog output signal, but few monitors are able to display the image. For this reason, capture boards are recommended to digitize the analog image for display.

Figure 1a: Ghosting and Blurring of TECHSPEC® Man's High-Speed Movement Using an Interlaced Scanning Sensor

Figure 1b: TECHSPEC® Man's High-Speed Movement Using a Progressive Scanning Sensor

Continue

AREA SCAN VS. LINE SCAN CAMERAS

In area scan cameras, an imaging lens focuses the object to be imaged onto the sensor array, and the image is sampled at the pixel level for reconstruction (Figure 2). This is convenient if the image is not moving quickly or if the object is not extremely large. Familiar digital point-and-shoot cameras are examples of area scan devices. With line scan cameras, the pixels are arranged in a linear fashion, which allows for very long arrays (Figure 2). Long arrays are ideal because the amount of information to be read-out per exposure decreases substantially and the speed of the readout increases by the absence of column shift registers or multiplexers; in other words, as the object moves past the camera, the image is taken line by line and reconstructed with software.

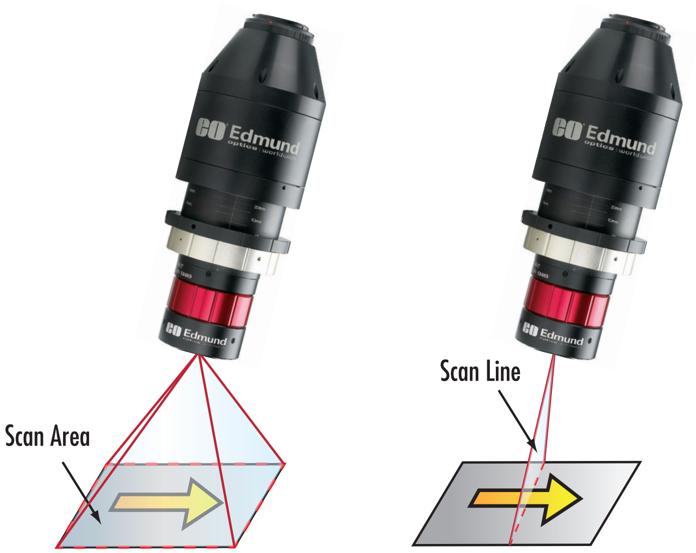


Figure 2: Illustration of Area Scanning Technique (left). Illustration of Line Scanning Technique (right)

Table 2: Comparison of Area Scan Cameras and Line Scan Cameras

Area Scan Cameras	Line Scan Cameras
4:3 (H:V) Ratio (Typical)	*Linear Sensor*
Large Sensors	*Large Sensor*
High-Speed Applications	*High-Speed Applications*
Fast Shutter Times	*Constructs Image One Line at a Time*
Lower Cost than Line Scan	*Object Passes in Motion Under Sensor*
Wider Range of Applications than Line Scan	*Ideal for Capturing Wide Objects*
Easy Setup	*Special Alignment and Timing Requires; Complex Integration but Simple Illumination*

TIME DELAY AND INTEGRATION (TDI) VS. TRADITIONAL LINE SCAN CAMERAS

In traditional line scan cameras, the object moves past the sensor and an image is made line by line. Since each line of the reconstructed image is from a single, short exposure of the linear array, very little light is collected. As a result, this requires substantial illumination (think of a copy machine or document scanner). The alternative is Time Delay and Integration (TDI) line scan cameras. In these arrangements, multiple linear arrays are placed side by side. After the first array is exposed, the charge is transferred to the neighboring line. When the object moves the distance of the separation between lines, a second exposure is taken on top of the first, and so on. Thus, each line of the object is imaged repeatedly, and the exposures are added to each other (Figures 3a - 3b). This reduces noise, thereby increasing signal. Also, it demonstrates the concept of triggering, wherein the exposure of a pixel array is synchronized with the motion of the object and the flash of the lighting.

TIME DELAY AND INTEGRATION (TDI) VS. TRADITIONAL LINE SCAN CAMERAS

Figure 3a (Left): The First Array is Exposed and the Charge is Transferred to the Neighboring Line

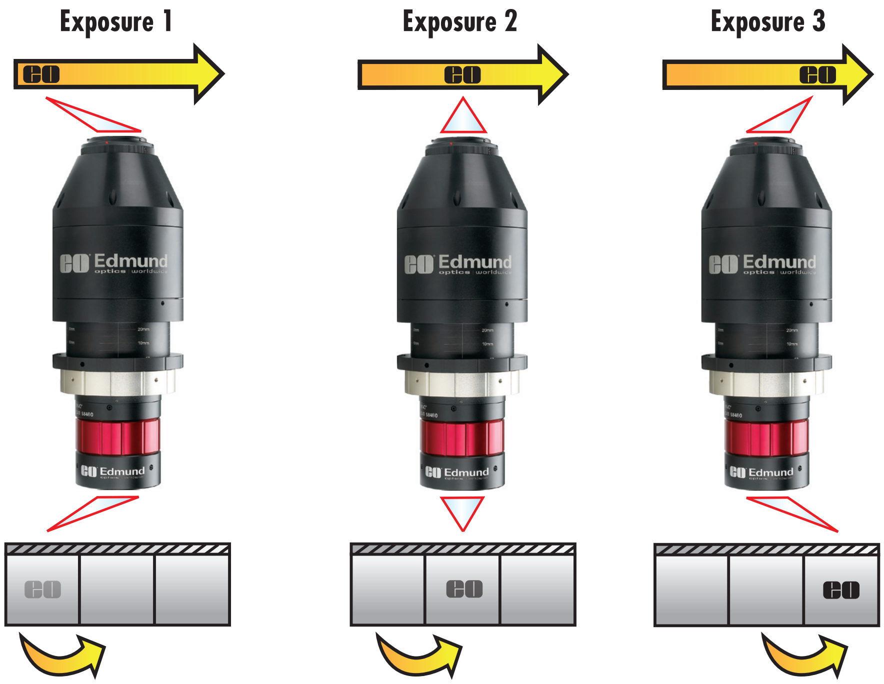


Figure 3c (Right): The Object Continues to Move the Separation between Lines until Each Line of the Object is Imaged

Figure 3b (Center): The Object Moves the Distance of the Separation between Lines and a Second Exposure is Taken on Top of the First

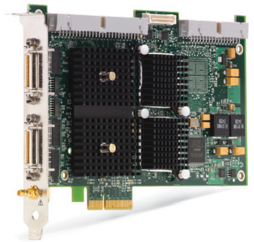
DIGITAL CAMERA INTERFACES

Digital cameras have gained in popularity over the past decade because transmission noise, distortion, or other signal degradations do not affect the information being transmitted. Since the output signal is digital, there is little information lost in the transmission process. As more and more users turn to digital cameras, imaging technology has also advanced to include a multitude of digital interfaces. The imaging landscape will be very different in another decade, but the most common interfaces available today are capture boards, Firewire, Camera Link®, GigE, and USB (Table 3).

As with many of the criteria for camera selection, there is no single best option interfaces, but rather one must select the most appropriate devices for the application at hand. Asynchronous or deterministic transmission allows for data transfer receipts, guaranteeing signal integrity, placing delivery over timing due to the two-way communication. In isochronous transmission, scheduled packet transfers occur (e.g. every 125μs), guaranteeing timing but allowing for the possibility of dropping packets at high transfer rates.

CAPTURE BOARDS

Image processing typically involves the use of computers. Capture boards allow users to output analog camera signals into a computer for analysis; or an analog signal (NTSC, YC, PAL, CCIR), the capture board contains an analog-to-digital converter (ADC) to digitize the signal for image processing. Others enable real time viewing of the signal. Users can then capture images and save them for future manipulation and printing. Basic capturing software is included with capture boards, allowing users to save, open, and view images. The term capture board also refers to PCI cards that are necessary to acquire and interpret the data from digital camera interfaces, but are not based on standard computer connectors.



Continue

FIREWIRE (IEEE 1394/IIDC DCAM STANDARD)

Firewire, aka IEEE 1394, is a popular serial, isochronous camera interface due to the widespread availability of Firewire ports on computers. Although Firewire.a is one of the slower transfer rate interfaces, both Firewire.a and Firewire.b allow for the connection of multiple cameras, and provide power through the Firewire cable. Hot-swap/hot-plugging is not recommended, as the connector's design may cause power pin shorting to signal pins, potentially damaging the port or the device.

CAMERALINK®

Cameralink® is a high speed serial interface standard developed explicitly for machine vision applications, most notably those that involve automated inspection and process control. A cameralink capture card is required for usage, and power must be supplied separately to the camera. Special cabling is required because, in addition to low-voltage differential pair LVDP signal lines, separate asynchronous serial communication channels are provided to retain full bandwidth for transmission. The single-cable base configuration allows 255 MB/s transfer dedicated for video. Dual outputs (full configuration) allow for separate camera parameter send/receive lines to free up more data transfer space (680 MB/s) in extreme high-speed applications.

CameraLink HS (High Speed) is an extension to the CameraLink interface that allows for much higher speed (up to 2100MB/s at 15m) by using more cables. Additionally, CameraLink HS incorperates support for fiber optic cables with lengths of up to approximately 300m.

GigE (GigE VISION STANDARD)

GigE is based on the gigabit ethernet internet protocol and uses standard Cat-5 and Cat-6 cables for a high-speed camera interface. Standard ethernet hardware such as switches, hubs, and repeaters can be used for multiple cameras, although overall bandwidth must be taken into consideration whenever non peer-to-peer (direct camera to card) connections are used. In GigE Vision, camera control registers are based on the EMVA GenICam standard. Optional on some cameras, Link Aggregation (LAG, IEEE 802.3ad) uses multiple ethernet ports in parallel to increase data transfer rates, and multicasting to distribute processor load. Supported by some cameras, the network Precision Time Protocol (PTP) can be used to synchronize the clocks of multiple cameras connected on the same network, allowing for a fixed delay relationship between their associated exposures. Devices are hot-swappable.

The GigE Vision standard also supports higher speed data transmission based on the 10GigE network standard. 10GigE has the potential to exceed the speed of CameraLink and USB 3.0 while still allowing for longer cable lengths.

USB (UNIVERTSAL SERIAL BUS)

USB 2.0 is a popular interface due to its ubiquity among computers. It is not high speed, but it is convenient; maximum attainable speed depends upon the number of USB peripheral components, as the transfer rate of the bus is fixed at 480MB/s total. Cables are readily available in any computer store. In some cases, as with laptop computers, it may be necessary to apply power to the camera separately.

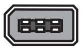
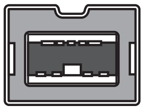
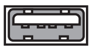
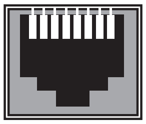
USB 3.0 features the plug-and-play benefits of USB 2.0, while allowing for much higher data transmission rates.

COAXPRESS

CoaXPress is a single cable high bandwidth serial interface that allows for up to 6.25 GB/s transmission rates with cable lengths up to 100m. Multiple cables can be used for speeds of up to 25 GB/s. Much like POE, Power-over-Coax is an available option, as well. A CoaXPress frame grabber is required.

DIGITAL CAMERA INTERFACES

Table 3: Comparison of Popular Digital Camera Interfaces

Interfaces	FireWire 1394.a	FireWire 1394.b	Camera Link®	USB 2.0	GigE
Illustration					
Maximum Data Transfer Rate	*400 Mb/s*	*800 Mb/s*	*3.6 GB/s (full configuration)*	*480 Mb/s*	*1000 Mb/s*
Maximum Cable Length	*4.5m*	*100m (with GOF cable)*	*10m*	*5m*	*100m*
Number of Devices	*up to 63*	*up to 63*	*1*	*up to 127*	*Unlimited*
Connector	*6pin-6pin*	*9pin-9pin*	*26pin*	*USB*	*RJ45/CAT5*
Capture Board	*Optional*	*Optional*	*Required*	*Optional*	*Not Required*
External Power	*Optional*	*Optional*	*Required*	*Optional*	*Required*

POWERING THE CAMERA

Many camera interfaces allow for power to be supplied to the camera remotely over the signal cable. When this is not the case, power is commonly supplied either through a HIROSE connector (which also allows for trigger wiring and I/O), or a standard AC/DC adapter type connection. Even in cases where the camera can be powered by card or port, using the optional power connection may be advantageous. For example, daisy chaining Firewire cameras or running a system from a laptop are ideal cases for additional power. Also, cameras that have large, high-speed sensors and on board FPGAs require more power than can be sourced through the signal cable.

POWER OVER ETHERNET (POE)

Currently, power injectors are available that allow, with particular cameras, the ability to deliver power to the camera over the GigE cable. This can be important when space restrictions do not allow for the camera to have its own power supply, as in factory floor installations or outdoor applications. In this case, the injector is added somewhere along the cable line with standard cables running to the camera and computer. However, not all GigE cameras are PoE compatible. As with other interfaces, if peak performance is necessary, the power should be supplied separately from the signal cable. In PoE, the supply voltage is based on a standard that uses a higher voltage than standard cameras can supply; this necessitates more electronics and causes more power dissipation which requires sophisticated thermal design to avoid an increase in thermal noise and thus loss of image quality.

Continue

ANALOG CCD OUTPUT SIGNAL

There are a few different formats for analog video signals. The format defines the frame rate, the number of display lines, time dedicated to display and blanking, synchronization, the bandwidth, and the signal specifics. In the United States, the Electronic Industries Association (EIA) defines the monochrome signal as RS-170. The color version is defined as RS-170A, more commonly known as National Television Standards Committee (NTSC). Both RS-170 and NTSC are composite signals. This means that all of the color and intensity information is combined into one signal. There are some component signals (Y-C and RGB) which separate chrominance (color) from luminance (color intensity). CCIR is the European monochrome standard while PAL and SECAM are the European color standards.

Note: The camera and display formats must be the same to get a proper image.

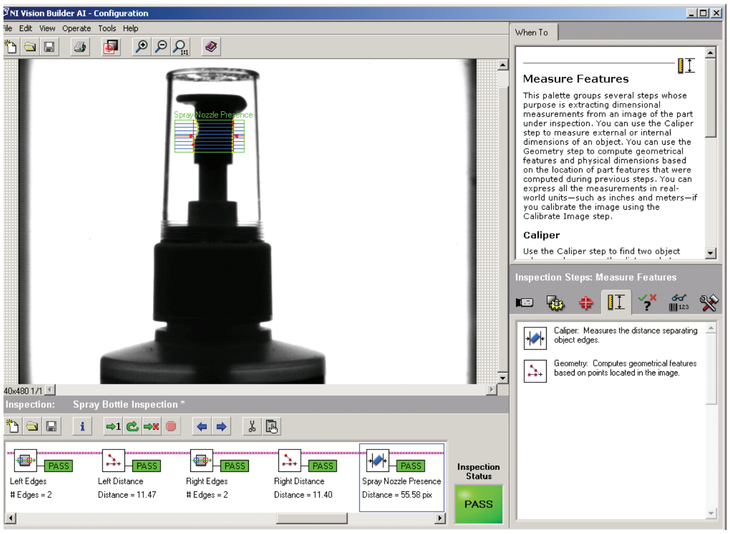
LAPTOPS AND CAMERAS

Although many digital camera interfaces are accessible to laptop computers, it is highly recommended to avoid standard laptops for high-quality and/or high-speed imaging applications. Often, the data busses on the laptop will not support full transfer speeds and the resources are not available to take full advantage of high performance cameras and software. In particular, the ethernet cards standard in most laptops perform at a much lower level than the PCIe cards available for desktop computers.

CAMERA SOFTWARE

In general, there are two choices when it comes to imaging software: camera-specific software development kits (SDKs) or third-party software. SDKs include application programming interfaces with code libraries for development of user defined programs, as well as simple image viewing and acquisition programs that do not require any coding and offer simple functionality. With third-party software, camera standards (GenICam, DCAM, GigE Vision) are important to ensure functionality. Third party software includes NI LabVIEW™, MATLAB®, OpenCV, and the like. Often, third-party software is able to run multiple cameras and support multiple interfaces, but it is ultimately up to the user to ensure functionality.

Though a host of camera types, interfaces, power requirements, and software exist for imaging applications, understanding the pros and cons of each allows the user to pick the best combination for any application. Whether an application requires high data transfer, long cable lengths, and/or daisy chaining, a camera combination exists to achieve the best results.



TELECENTRICITY AND TELECENTRIC LENSES IN MACHINE VISION

The increased popularity of imaging technology over the last decade has spurred the demand for a wide variety of lenses that can provide optical designers with images suitable for all types of analysis. One such example is the telecentric lens, which is frequently used in the machine vision industry for measurement and alignment applications. In order to understand what makes telecentric lenses ideal for machine vision, it is important to look at what it means to be telecentric, compare telecentric lenses to conventional lenses, and examine the most common applications involving telecentricity.

WHAT IS TELECENTRICITY?

Telecentricity is a unique property of certain multi-element lens designs in which the chief rays are collimated and parallel to the optical axis in image and/or object space. A key characteristic of telecentricity, then, is constant magnification regardless of image and/or object location. There are three classifications of telecentricity depending upon the optical space(s) in which the chief rays exhibit this behavior.

CLASSIFICATION 1: OBJECT-SPACE TELECENTRICITY

It occurs when the system stop is placed at the front focal plane of the lens, resulting in an entrance pupil location at infinity. A shift in the object plane does not affect image magnification.

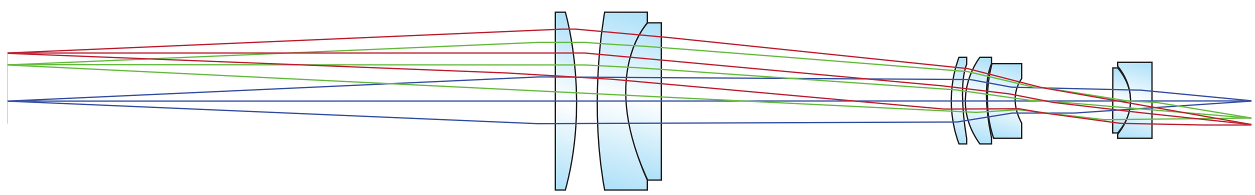


Figure 1: 0.5X Object-Space Telecentric Lens (Note the Parallel Chief Rays in Object Space)

CLASSIFICATION 2: IMAGE-SPACE TELECENTRICITY

It occurs when the system stop is placed at the rear focal plane of the lens, resulting in an exit pupil location at infinity. A shift in the image plane does not affect image magnification.

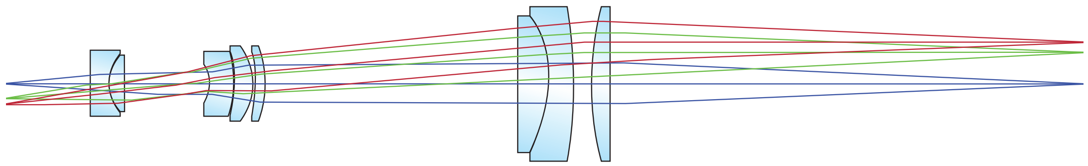


Figure 2: 0.5X Image-Space Telecentric Lens (Note the Parallel Chief Rays in Image Space)

CLASSIFICATION 3: DOUBLE TELECENTRICITY

Also known as bilateral telecentricity, it occurs when the system stop is placed at the common focal plane, resulting in both the entrance and exit pupils being located at infinity. Shifting either the image or object planes does not affect magnification given that double telecentric systems are afocal.

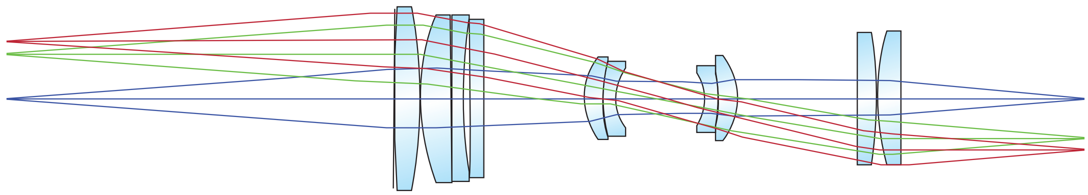


Figure 3: 0.9X Double Telecentric Lens (Note the Parallel Chief Rays in Both Image and Object Spaces)

TELECENTRIC LENSES VS. CONVENTIONAL LENSES

Perspective error, also called parallax, is part of everyday human experience. In fact, parallax is what allows the brain to interpret the 3-D world. In other words, we expect close objects to appear relatively larger than those placed farther away. Conventional lenses are those which exhibit this phenomenon, wherein the magnification of an object changes according to its distance from the lens (Figure 4). This occurs because the chief rays in this system are not all parallel to the optical axis (Figure 5). Telecentric lenses, by contrast, optically correct for parallax so that objects remain the same perceived size independent of their distance, over a range defined by the lens.

There is a common misconception that telecentric lenses have a larger depth of field than conventional lenses. Realistically, telecentricity does not imply large depth of field, which is only dependent on f-number and resolution. With telecentric lenses, objects still blur farther away from best focus, but they blur symmetrically. This symmetrical blurring holds the centroid position constant, allowing for accurate edge and feature location even when the image is not in focus.

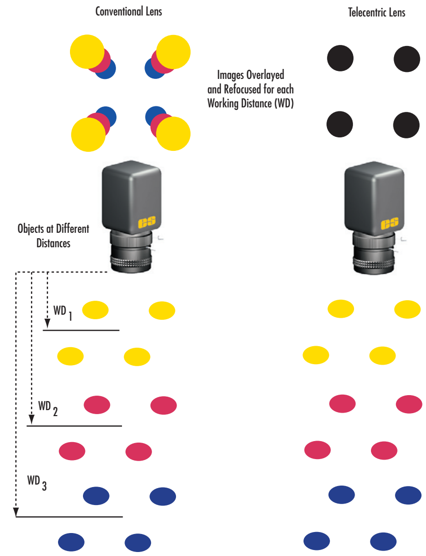


Figure 4: Reduced Perspective Error in Telecentric Lens vs. Conventional Lens

Continue

ADVANTAGES AND DISADVANTAGES OF TELECENTRIC LENSES

- Use of large aperture optical elements in the region of telecentricity (image space or object space) in order to provide a non-vignetted field of view
- Use of more optical elements (due to the complex design) than conventional lens systems
- Increase in cost and weight because of large aperture and more optical elements

Advantages of Telecentric Lenses
- Reduction or elimination of perspective error
- Reduction in distortion
- Increase in image resolution
- Uniform image plane illumination - An additional advantage of image space telecentricity is that it can lead to extremely uniform image plane illumination. The normal $\cos^4\theta$ falloff in image plane illumination from the optical axis to the edge of the field is removed, since all chief rays have an angle of θ with respect to the image plane.
- Constant magnification independent of shift in image and/or object planes

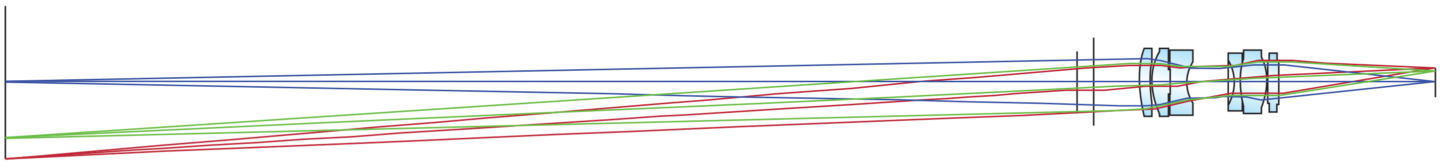


Figure 5: 75mm FL Conventional Lens (Note the Chief Rays in Both Image and Object Spaces are NOT Parallel)

APPLICATION EXAMPLES

Despite the disadvantages inherent to the increased complexity of telecentric lens design, the numerous benefits make telecentric lenses a popular choice in a variety of applications. In particular, telecentric lenses are commonly used in machine vision applications where software analysis is simplified and more accurate because of the reduction of parallax. In addition, general applications range from inspecting pipes to measuring object thickness.

APPLICATION 1: ALIGNMENT OF JUMPER PINS

As electrical components become smaller and smaller, the level of precision needed in aligning them becomes that much greater. When dealing with such minute detail, the perspective error created by a conventional lens becomes a more prevalent factor.

Figures 6 - 7 show a series of pins as imaged through a telecentric lens and a conventional lens. Notice how the conventional lens images the sides and bases of the pins that are off-axis (Figure 7). Comparatively, the telecentric lens only images the tops of the pins regardless of their location on the image plane (Figure 6).

Continue

APPLICATION 1: ALIGNMENT OF JUMPER PINS (CONT.)

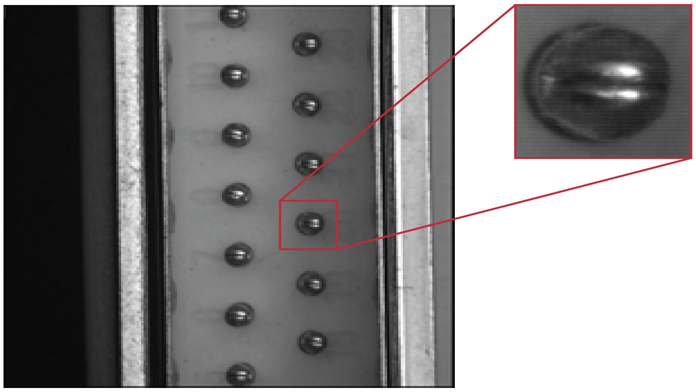


Figure 6: Telecentric Lens Imaging Jumper Pins

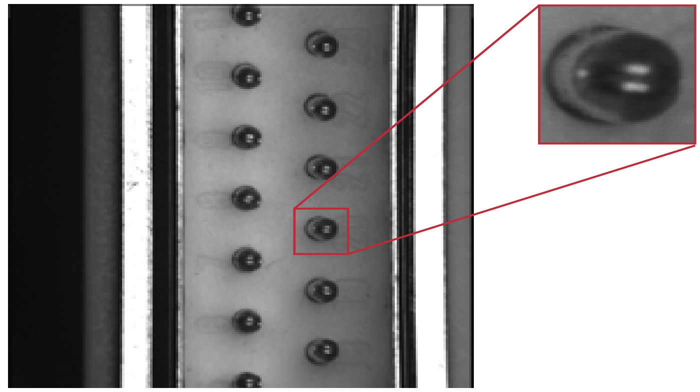


Figure 7: Conventional Lens Imaging Jumper Pins

APPLICATION 2: CCD BASED MEASUREMENT

CCD based measurement systems can be used to measure the spacing and/or size of a number of objects on an electrical or mechanical component. The precise measurement of objects (such as a pin) or features, or their separations, is accomplished through the use of measurement software. This type of software uses centroiding algorithms in the calculations of object separation and size. A telecentric lens is ideal for this application because extended objects will appear symmetrical (Figure 8), whereas the image from a conventional lens will be elliptical (Figure 9). Using a telecentric lens for this type of edge detection analysis results in an accurate circular fit to the pin, reducing error in the prediction of its center.

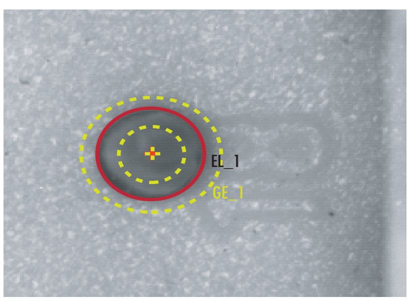


Figure 8: Telecentric Lens Imaging Extended Object

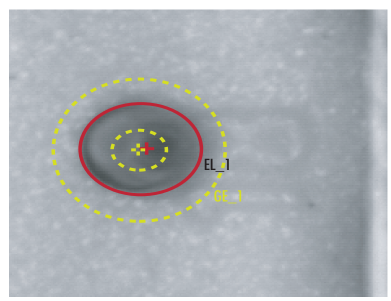


Figure 9: Conventional Lens Imaging Extended Object

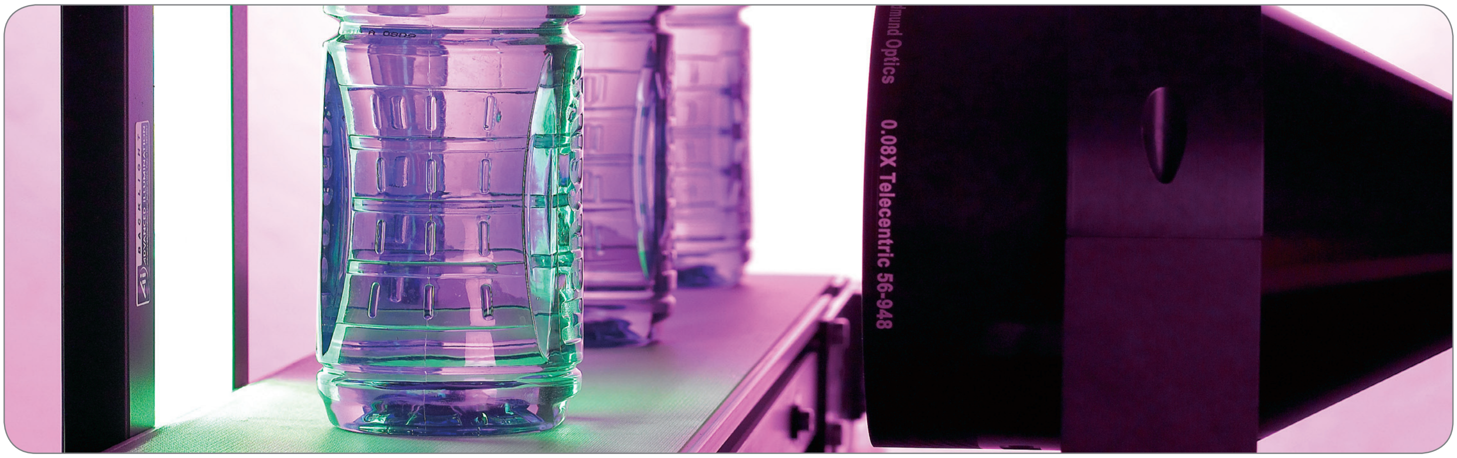
APPLICATION 3: METROLOGY

Many metrology systems also depend upon telecentric optics. A profile projector is one example of such a system. Profile projectors are used to measure an object, or a feature within an object, by projecting an image of the area under test onto a screen. This projected image is then either compared to a "gold standard" reference at the proper magnification. This type of measurement requires equal magnification on two separate object planes for the comparison to be accurate - a task well suited to telecentric lenses.

APPLICATION 4: MICROLITHOGRAPHY

Microlithographic lens systems are used in the etching of integrated circuits onto wafers. The features inherent to these circuits are routinely sub-micron in size and getting smaller with every new generation of microlithographic equipment. The size of these features, along with their absolute locations, must be controlled to small fractions of a micron. This problem is intensified by the overlay necessary when numerous resist exposures and etches are required in the production process.

CHOOSE THE CORRECT ILLUMINATION



Often, a customer struggles with contrast and resolution problems in an imaging system, while underestimating the power of proper illumination. In fact, desired image quality can typically be met by improving a system's illumination rather than investing in higher resolution detectors, imaging lenses, and software. System integrators should remember that proper light intensity in the final image is directly dependent upon component selection.

Correct illumination is critical to an image system and improper illumination can cause a variety of image problems. Blooming or hot spots, for example, can hide important image information, as can shadowing. In addition, shadowing can also cause false edge calculations when measuring, resulting in inaccurate measurements. Poor illumination can also result in a low signal-to-noise ratio. Non-uniform lighting, in particular, can harm signal-to-noise ratios and make tasks such as thresholding more difficult. These are only a few of the reasons why correct illumination for your application is so important.

The pitfalls of improper illumination are clear, but how are they avoided? To ensure optimal illumination when integrating a system, it is important to recognize the role that choosing the right components plays. Every component affects the amount of light incident on the sensor and, therefore, the system's image quality. The imaging lens' aperture (f/#) impacts the amount of light incident on the camera. Illumination should be increased as the lens aperture is closed (i.e. higher f/#). High power lenses usually require more illumination, as smaller areas viewed reflect less light back into the lens. The camera's minimum sensitivity is also important in determining the minimum amount of light required in the system. In addition, camera settings such as gain, shutter speed, etc., affect the sensor's sensitivity. Fiber optic illumination usually involves an illuminator and light guide, each of which should be integrated to optimize lighting at the object.

The light intensity for our illumination products is typically specified in terms of footcandles (English unit). Lux, the SI unit equivalent, can be related to footcandles as follows: 1 lux = 0.0929 footcandle.

Table 1: Key Photometric Units

1 footcandle	*= 1 lumen/ft^2*
1 footcandle	*= 10.764 meter candles*
1 footcandle	*= 10.764 lux*
1 candle	*= 1 lumen/steradian*
1 candle	*= 3.142 x 10^{-4} Lambert*
1 Lambert	*= 2.054 candle/in^2*
1 Lux	*= meter candle*
1 Lux	*= 0.0929 footcandle*
1 meter candle	*= 1 lumen/m^2*

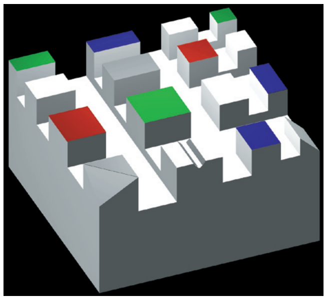
Table 2: Illumination Comparison

Application Requirements	Object Under Inspection	Suggested Type of Illimination
Reduction of specularity	*Shiny object*	*Diffuse front, diffuse axial, polarizing*
Even illumination of object	*Any type of object*	*Diffuse front, diffuse axial, ring light*
Highlight surface defects or topology	*Nearly flat (2-D) object*	*Single directional, structured light*
Highlight texture of object with shadows	*Any type of object*	*Directional, structured light*
Reduce shadows	*Object with protrusions, 3-D object*	*Diffuse front, diffuse axial, ring light*
Highlight defects within object	*Transparent object*	*Darkfield*
Silhouetting object	*Any type of object*	*Backlighting*
3-S shape profiling of object	*Object with protrusions, 3-D object*	*Structured light*

Continue

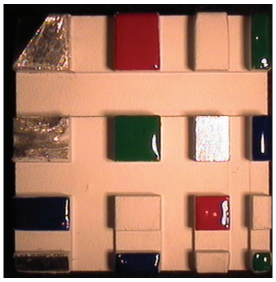
TYPES OF ILLUMINATION

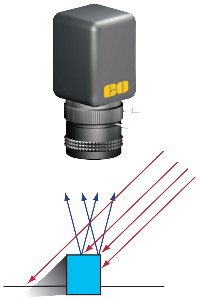
Since proper illumination is often the determining factor between a system's success and failure, many specific products and techniques have been developed to overcome the most common lighting obstacles. The target used throughout this section was developed to demonstrate the strengths and weaknesses of these various lighting schemes for a variety of object features. The grooves, colors, surface deformations, and specular areas on the target represent some of the common trouble areas that may demand special attention in actual applications.



DIRECTIONAL ILLUMINATION

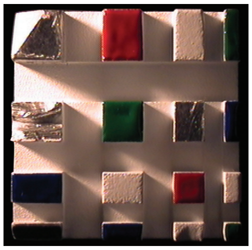
Directional Illumination - Point source illumination from single or multiple sources. Lenses can be used to focus or spread out illumination.	
Pros	*Bright, flexible, and can be used in various applications. Easily fit into different packaging.*
Cons	*Shadowing and glare.*
Useful Products	*Fiber optic light guides, focusing assemblies, LED spot lights, and incandescent light.*
Application	*Inspection and measurement of matte and flat objects.*

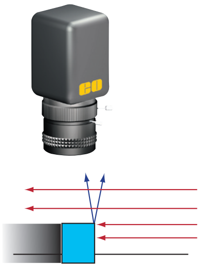




DIRECTIONAL ILLUMINATION

Glancing Illumination - Point source illumination similar to directional illumination, except at a sharp angle of incidence.	
Pros	*Shows surface structure and enhances object topography.*
Cons	*Hot spots and extreme shadowing.*
Useful Products	*Fiber optic light guides, focusing assemblies, LED spot lights, and incandescent light and line light guides.*
Application	*Identifying defects in an object with depth and examining finish of opaque objects.*





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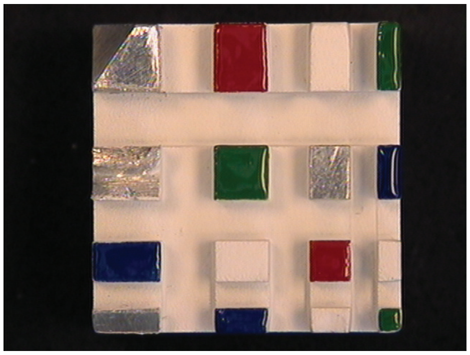
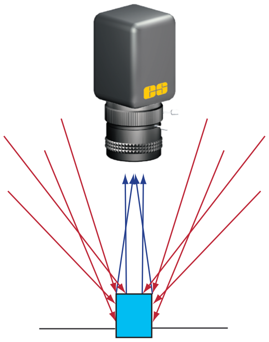
DIFFUSE ILLUMINATION

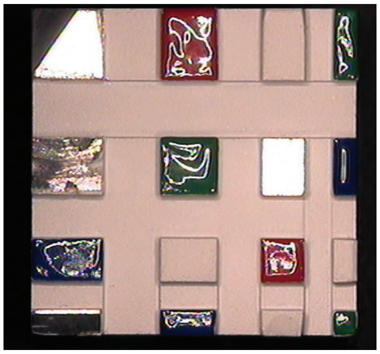
Diffuse Illumination - Diffuse, even light from an extended source.	
Pros	*Reduces glare and provides even illumination.*
Cons	*Large and difficult to fit into confined spaces.*
Useful Products	*Fluorescent linear lights.*
Application	*Best for imaging large, shiny objects with large working distances.*

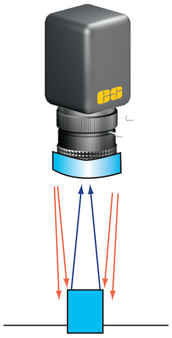




RING LIGHT

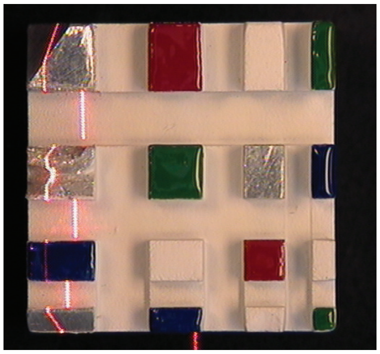
Ring Light - Coaxial illumination that mounts directly on a lens.	
Pros	*Mounts directly to lens and reduces shadowing. Uniform illumination when used at proper distances*
Cons	*Circular glare pattern from reflective surfaces. Works only in relatively short working distances.*
Useful Products	*Fiber optic ring light guides and fluorescent ring lights; LED ring lights.*
Application	*Wide variety of inspection and measurement systems with matte objects.*

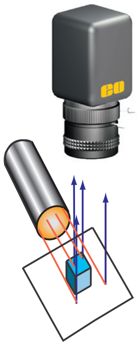




STRUCTURED LIGHT (LINE GENERATORS)

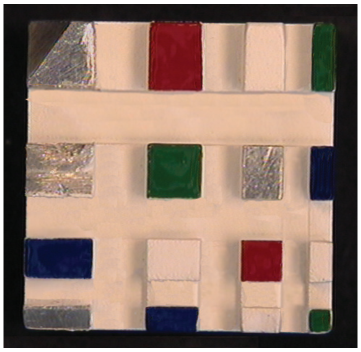
Structured Light (Line Generators) - Patterns that are projected onto the object. Typically laser projected lines, spots, grids, or circles.	
Pros	*Enhances surface features by providing intense illumination over a small area. Can be used to get depth information from object.*
Cons	*May cause blooming and is absorbed by some colors.*
Useful Products	*Lasers with line generative or diffractive pattern generating optics.*
Application	*Inspection of three-dimensional objects for missing features. Topography measurements.*

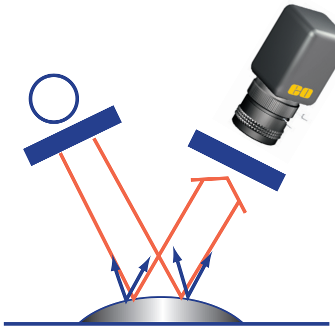




POLARIZED LIGHT

Polarized Light - A type of directional illumination that makes use of polarized light to remove specularities and hot spots.	
Pros	*Provides even illumination over the entire surface of the object under polarization. Reduces glare to make surface features discernable.*
Cons	*Overall intensity of light is reduced after polarization filter is placed in front of light source and/or imaging lens.*
Useful Products	*Polarization filters and Polarizer/Analyzer adapters.*
Application	*Measurements and inspection of shiny objects.*





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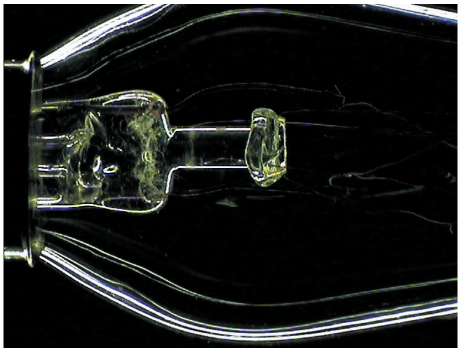
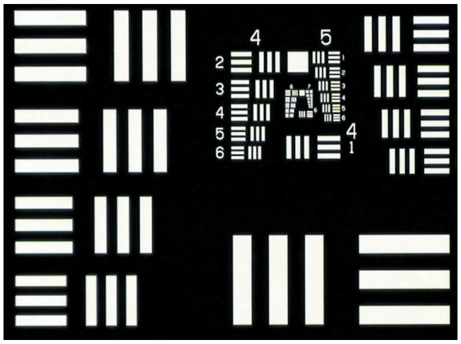
DARKLIGHT

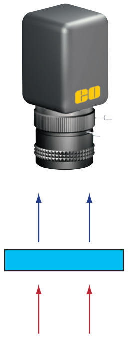
Darklight - Light enters a transparent or translucent object through the edges perpendicular to the lens.	
Pros	*High contrast of internal and surface details. Enhances scratches, cracks, and bubbles in clear objects.*
Cons	*Poor edge contrast. Not useful for opaque objects.*
Useful Products	*Fiber optic darkfield attachment, line light guides, and laser line generators.*
Application	*Glass and plastic inspection.*



BRIGHTFIELD/BACKLIGHT

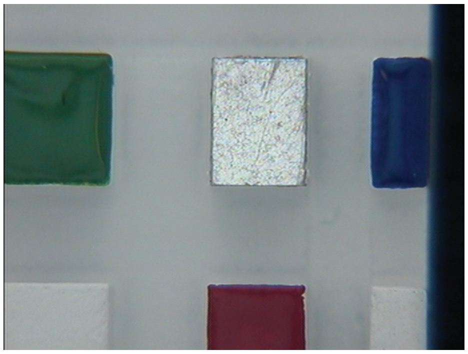
Brightfield/Backlight- Object is lit from behind. Used to silhouette opaque objects or for imaging through transparent objects.	
Pros	*High contrast for edge detection.*
Cons	*Eliminates surface detail.*
Useful Products	*Fiber optic backlights and LED backlights.*
Application	*Targets and test patterns, edge detection, measurement of opaque objects and sorting of translucent colored objects.*

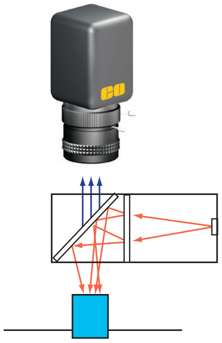




DIFFUSE AXIAL ILLUMINATION

Diffuse Axial Illumination - Diffuse light in-line with the optics. Lens looks through a beamsplitter that is reflecting light onto the object. Illumination is coaxial to imaging access.	
Pros	Very even and diffuse; greatly reduces shadowing; very little glare.
Cons	Large and difficult to mount; limited working distance; low throughput such that multiple fiber optic sourced may be needed to provide sufficient illumination.
Useful Products	Fiber optic diffuse axial attachment. Single or multiple fiber optic illuminators. Single, dual, or quad fiber bundles depending on size of attachment and number of illuminators used. LED diffuse axial illuminator.
Application	Measurements and inspection of shiny objects.



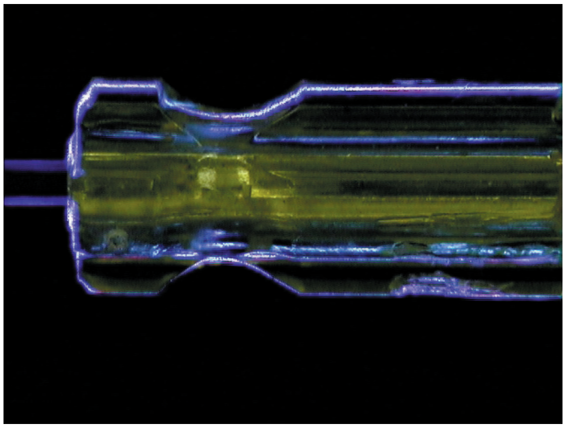


FILTERING PROVIDES VARIOUS LEVELS OF CONTRAST

Examples illustrate darkfield and backlight illumination with assorted color filters. Note: Images taken with 10X Close Focus Zoom Lens #54-363: Field of View = 30mm, Working Distance = 200mm.

Darkfield Only: Defects appear white.

Darkfield with Blue Filter: Defects appear blue.



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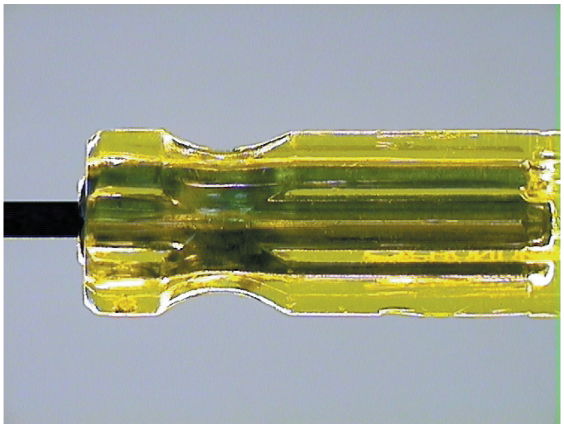
FILTERING PROVIDES VARIOUS LEVELS OF CONTRAST (CONT.)



Darkfield and Backlight: No filter used, but edge contrast improves

Darkfield without Filter and Backlight with Yellow Filter: Enhances overall contrast, defects appear white in contrast to rest of field.

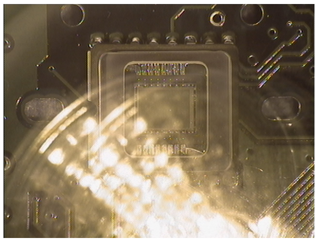
IMAGE ENHANCEMENT USING POLARIZERS

A polarizer is useful for eliminating specular reflections (glare) and bringing out surface defects in an image. A polarizer can be mounted either on the light source, on the video lens, or on both depending upon the object under inspection. When two polarizers are used, one on the illumination source and one on the video lens, their polarization axes must be oriented perpendicular to each other. The following are polarization solutions to glare problems for several material types and circumstances.

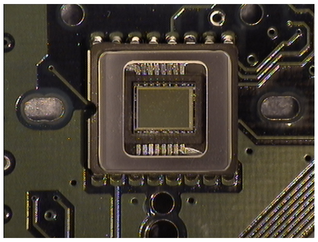
Problem 1:
The object is non-metallic and illumination strikes it at a sharp angle.

Solution 1:
A polarizer on the lens is usually sufficient for blocking glare. (Rotate the polarizer until glare is at a minimum.) Add a polarizer in front of the light source if glare is still present.

Without Polarizers



Using Polarizers



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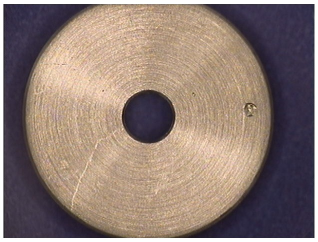
Problem 2:
The object has a metallic or shiny surface.

Solution2:
Mounting a polarizer on the light source as well as on the lens is recommended for enhancing contrast and bringing out surface details. The polarized light incident on the shiny surface will remain polarized when it's reflected. Surface defects in the metal will alter the polarization of the reflected light. Turning the polarizer on the lens so its polarization axis is perpendicular to that of the illumination source will reduce the glare and make scratches and digs in the surface visible.

Without Polarizers

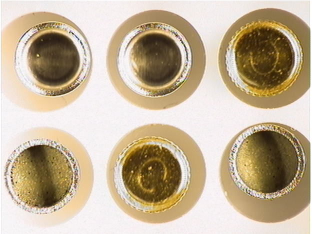
Using Polarizers



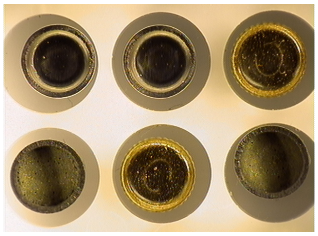
Problem 3:
The object has both highly reflective and diffuse areas.

Solution 3:
Using two polarizers with perpendicular orientation will eliminate hot spots in the image caused by the metallic parts. The rest of the field will be evenly illuminated due to the diffuse areas reflecting randomly polarized light to the lens.

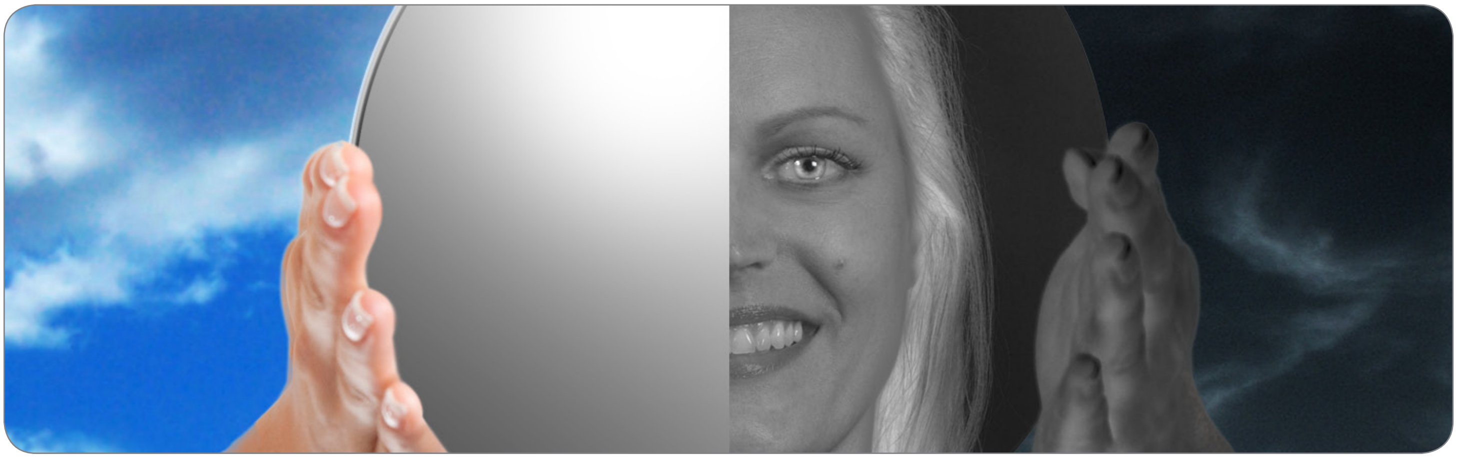
Without Polarizers



Using Polarizers



WHAT IS SWIR?



Short-wave infrared (SWIR) light is typically defined as light in the 0.9 – 1.7μm wavelength range, but can also be classified from 0.7 – 2.5μm. Since silicon sensors have an upper limit of approximately 1.0μm, SWIR imaging requires unique optical and electronic components capable of performing in the specific SWIR range. Indium gallium arsenide (inGaAs) sensors are the primary sensors used in SWIR imaging, covering the typical SWIR range, but can extend as low as 550nm to as high as 2.5μm. Although linear line-scan inGaAs sensors are commercially available, area-scan inGaAs sensors are typically ITAR restricted. ITAR, International Treaty and Arms Regulations, is enforced by the government of the United States of America. ITAR restricted products must adhere to strict export and import regulations for them to be manufactured and/or sold within and outside of the USA. Nevertheless, lenses such as SWIR ones can be used for a number of commercial applications with proper licenses.

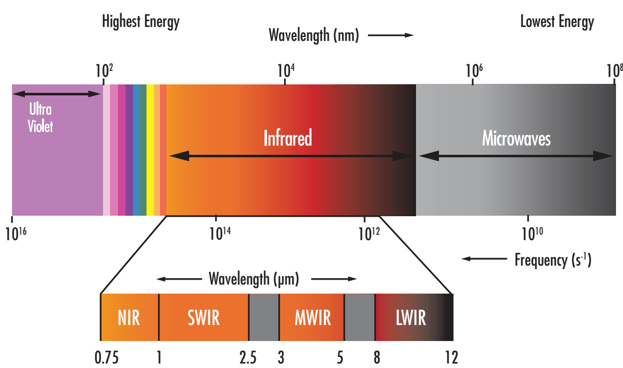


Figure 1: Electromagnetic Spectrum Illustrating SWIR Wavelength Range

WHY USE SWIR?

Unlike Mid-Wave Infrared (MWIR) and Long-Wave Infrared (LWIR) light, which is emitted from the object itself, SWIR is similar to visible light in that photons are reflected or absorbed by an object, providing the strong contrast needed for high resolution imaging. Ambient star light and background radiance (nightglow) are natural emitters of SWIR and provide excellent illumination for outdoor, nighttime imaging.

Continue

WHY USE SWIR? (CONT.)

It is essential to use a lens that is designed, optimized, and coated for the SWIR wavelength range. Using a lens designed for the visible spectrum will result in lower resolution images and higher optical aberrations. Since SWIR wavelengths transmit through glass, lenses, and other optical components (optical filters, windows, etc.) designed for SWIR can be manufactured using the same techniques used for visible components, decreasing manufacturing cost and enabling the use of protective windows and filters within a system.

A large number of applications that are difficult or impossible to perform using visible light are possible using SWIR. When imaging in SWIR, water vapor, fog, and certain materials such as silicon are transparent. Additionally, colors that appear almost identical in the visible may be easily differentiated using SWIR.

SWIR APPLICATIONS

SWIR imaging is used in a variety of applications including electronic board inspection, solar cell inspection, produce inspection, identifying and sorting, surveillance, anti-counterfeiting, process quality control, and much more. To understand the benefits of SWIR imaging, consider some visual examples of common, everyday products imaged with visible light and with SWIR.

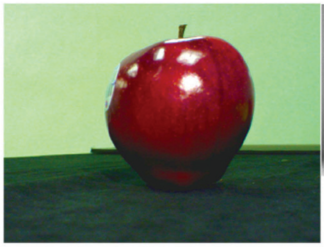


Figure 2a: Visible Imaging of Red Apple. Notice the Apple Looks Perfectly Red with Visible Imaging. Defects are Not Easiy Discernable.

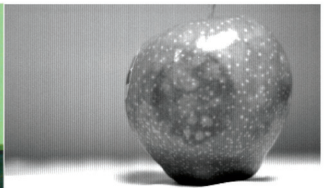


Figure 2b: SWIR Imaging of Red Apple. Bruising is Clearly Evident on the Apple with SWIR Imaging. It is Easy to Inspect Any Defects on the Skin.

Figure 3a: Visible Imaging of Baby Powder Bottle. Noticle the Bottle Looks White and Glossy with Visible Imaging. The Powder withing is not Discernable at All.

Figure 3b: SWIR Imaging of Baby Powder Bottle. The Bottle is Transparent to SWIR Wavelengths. It is Easy to See the Amount of Powder Within.

Short-wave infrared (SWIR) defines a specific wavelength range over which optical and electronic components are designed and coated. SWIR imaging offers a number of advantages compared to visible when used for inspection, sorting, surveillance, quality control, and host of other applications. It is important to choose components specifically designed, optimized, and coated for the SWIR wavelength range to ensure the highest resolution and lowest aberrations. Manufacturers like Edmund Optics are experienced in designing, manufacturing, and coating SWIR lenses. Edmund Optics offers lens assemblies designed with glasses that are optimized for performance in the SWIR spectrum, and anti-reflection (AR) coatings for SWIR specially designed for maximum transmission of SWIR wavelengths.