LUMENERA **WHITE PAPER SERIES**

DESIGNING A VISION SYSTEM

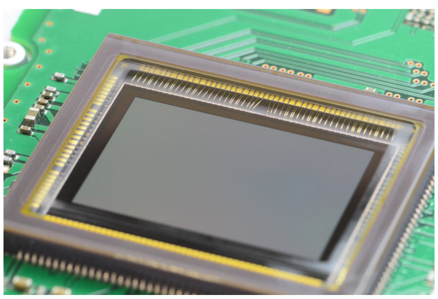
A Comprehensive Guide to the Technical Requirements for Building a Vision System for Your Unique Imaging Application

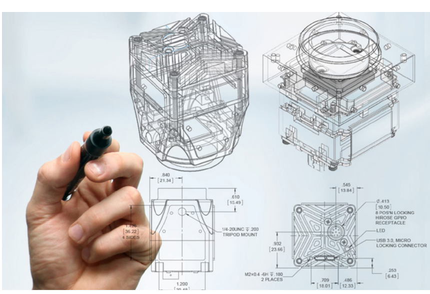
7 CAPELLA COURT, OTTAWA, ON, CANADA K2E 8A7 | TEL (613) 736-4077 | FAX (613) 736-4071 | WWW.LUMENERA.COM | INFO@LUMENERA.COM

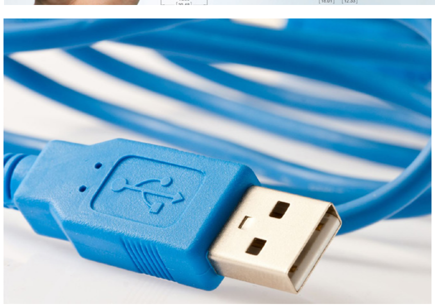
WWW.LUMENERA.COM

LUMENERA **WHITE PAPER SERIES**

DESIGNING A VISION SYSTEM







WHAT'S INSIDE

INTRODUCTION: DESIGNING A VISION SYSTEM

There are a number of factors that need to be considered when designing a vision system, including: the hardware platform, the operating system, the software and API, and the very things that make the vision system "see" – the camera and its lens. Although each aspect plays an important role in achieving desired results, the camera and lens are the essence of the vision system. As such, it is recommended that both the camera and the lens be selected as a pair based on overall system requirements. Here we discuss various elements of vision systems with a focus on the camera and lens.

LENSES & OPTICS

The lens and the camera have individual strengths that should be taken into consideration when it comes to capturing image data. For instance, selecting a camera with a high resolution sensor places less demand on the lens for magnification as the image can be enlarged digitally. This allows for the selection of a lens with a larger field of view to capture more information in a single frame. Alternatively, if the camera you are using doesn't have a high resolution sensor, you could select a lens with a longer focal length to obtain the detail required for your application.

WORKING DISTANCE & FIELD OF VIEW

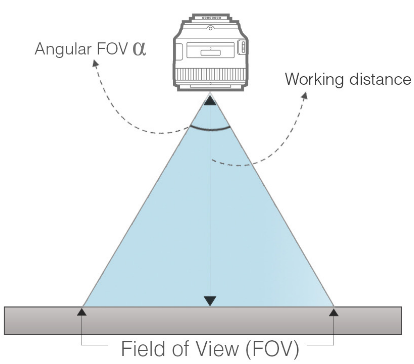
One of the most stringent design constraints in a vison system is the working distance. Based on the specific application requirements, there are often design limitations placed on the maximum or minimum distance the camera must be from its target due to the geometry of the setup.

Working Distance:
The distance between the front of the lens and the object to be imaged.

Likewise, the field of view is another important consideration. Regardless of the distance from the camera to the target, the amount of the scene to be imaged is also often critical to the application. This is where lens selection can optimize the system's performance.

Field of View:
The amount of area to be imaged by the camera in a single frame.

The field of view (FoV) and the working distance (WD) share a basic trigonometric relationship dependant on the angular field of view (α – in degrees) of the system. This relationship can be observed in the following figure, and calculated in the following equation:



$$\frac{FoV}{2 \times WD} = \tan\left(\frac{\alpha}{2}\right)$$

Where the angular field of view of the system shares a relationship between the focal length of the lens (f) and the size of the image sensor (d), as shown by the following equation:

$$\alpha = 2\arctan\left(\frac{d}{2f}\right)$$

For example, a camera with a 1 inch optical format sensor and a 12 mm lens placed 1 m from the target will have a horizontal field of view of 1041 mm and a vertical field of view of 833 mm[1]. The horizontal angular field of view can be determined knowing that the horizontal dimension of the sensor is 12.8 mm:

$$\alpha = 2\arctan\left(\frac{12.8}{2 \times 12}\right)$$

$$\alpha = 56.145°$$

Substituting to determine the horizontal field of view:

$$FoV = 2 \times 1 \times \tan\left(\frac{56.145}{2}\right)$$

$$FoV = 1.067m$$

And similarly, by knowing the vertical dimension of the sensor is 9.3 mm:

$$\alpha = 2\arctan\left(\frac{9.3}{2 \times 12}\right)$$

$$\alpha = 42.3627°$$

Substituting to determine the vertical field of view:

$$FoV = 2 \times 1 \times \tan\left(\frac{42.3627}{2}\right)$$

$$FoV = 0.775m$$

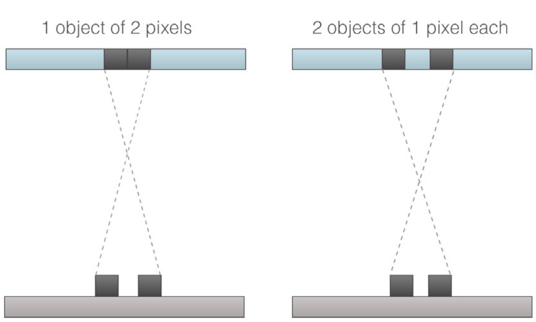
It is important to select a lens that can focus within the working distance and can attain the field of view necessary for the application. A balance between the two is often required to obtain acceptable results.

[1]These calculations are approximate and the actual working distance should be measured when the complete system is put into place.

CONTRAST & MODULATION TRANSFER FUNCTION

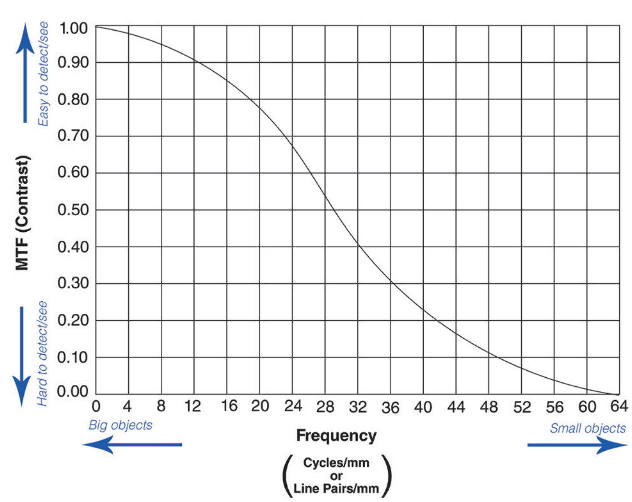
A common misconception is that the imaging system will be able to see a number of objects equal to its number of pixels. This is simply not the case as object detection, commonly done through edge detection, requires a line pair – an area of contrast with which to compare the object. High contrast is achieved when the difference between two colors is highly distinguishable; the simplest and highest contrast example is black and white. When contrast is lowered, it becomes harder to distinguish where one color (or object) ends and another begins; for instance a gradient of shades of gray between black and white.

Knowing that the sensor needs a high contrast space between objects for proper detection, the ideal case is that the camera can see a number of objects that is equal to half of its number of pixels, as defined by the Nyquist limit. In this case, each object would line up with a pixel on the image sensor and the high-contrast space between them with adjacent pixels. This is illustrated in the graphic below where the image sensor (in blue) in the left image does not have enough pixels to distinguish both objects – they appear as a single, larger object. The image sensor on the right has enough pixels to resolve both objects as well as the space between them therefore conforming to the Nyquist limit.



In reality, there are other factors within the design of the lens that will dictate the size and spatial frequency with which the objects appear in the frame for proper detection. These factors are typically illustrated in the lens' Modulation Transfer Function (MTF), which plots the contrast seen in the recorded image to the spatial frequency of an object. The MTF indicates the spatial frequency in line pairs per millimetre (lp/mm) and the contrast in terms of percentage. An example plot is shown below annotated with arrows in blue to help describe the values on each axis.

MTF vs. FREQUENCY



Modulation Transfer

A function illustrating the system's contrast in relation to the spatial frequency of objects to be imaged.

When selecting a lens, price is not always indicative of its performance. On a larger scale, a $1,000 lens will typically perform better than a $100 lens, but a $1,100 might not be better than a $1,000 lens.

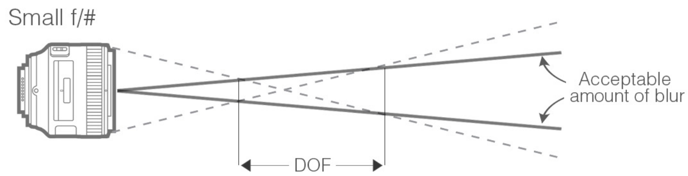
Since most lenses are designed to work within a specific range of working distances with MTF performance varying beyond these distances, it is important to match the lens' performance to the intended usage. MTF curves are a great tool for selecting a lens, as they combine contrast and resolution performance into a single specification. However, it is important to test the lens with the prospective camera to ensure required performance is met for a given application.

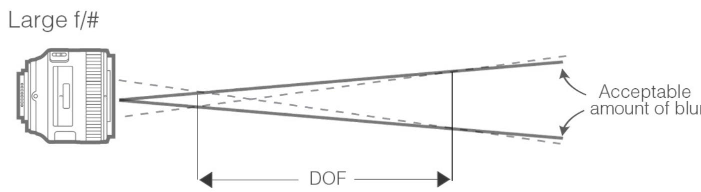
DEPTH OF FIELD

Certain applications require an object to be in focus within a varying working distance, without changing the focus of the lens. This can be achieved by taking advantage of a lens' depth of field.

Depth of Field:

Range of distance in front of the camera where the target remains in focus.





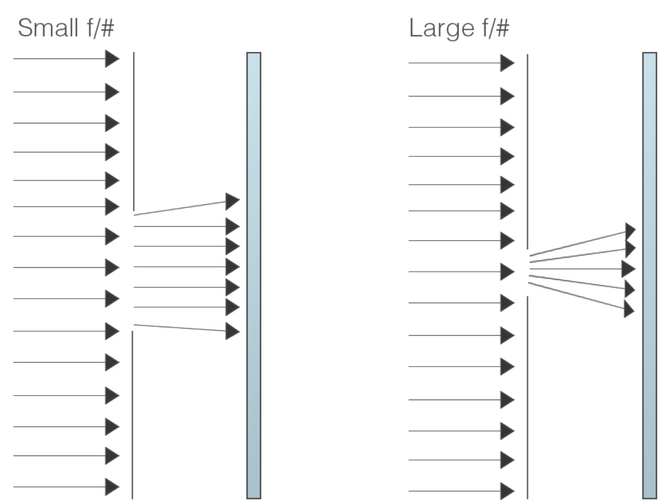
The depth of field is directly tied to the opening of the lens' aperture, measured in f-number or f-stop. This number (N) is a ratio between the focal length of the lens (f) and the opening diameter (D) of the aperture, given by the following expression:

$$N = \frac{f}{D}$$

The f-number can be written as 1:N, f:N, or f/N, and is often found on the lens. Since the diameter is the denominator of the fraction, a larger f number corresponds to a smaller aperture opening, thus allowing less light to pass through the lens.

Aside from managing the amount of light that passes through the lens, the size of the aperture will also impact both the resolution and the depth of field of the image. As the f-number is increased and the size of the aperture decreases, oblique light rays with high incidence angles are prevented from passing through the lens. The lens aberrations associated with these rays are the primary reason that an image is blurry outside of its depth of field. By eliminating these rays, the depth of field of the image can increase to cover a larger range.

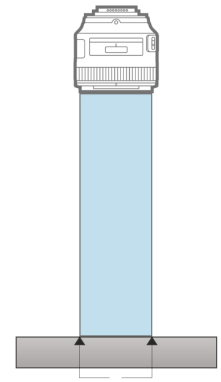
Conversely, when the f-number is decreased, the resolution of the image within its depth of field increases, creating a sharper image. This is due to an increase in the diffraction limit. As light passes through the aperture the rays diverge from their incident axis and spread out. Increasing the aperture diameter reduces this effect, allowing for a tighter grouping of the incident rays, thus producing a higher resolution image.



A trade-off between acceptable depth of field and resolution for the imaging system must be determined as the aperture drives these phenomena in opposite directions.

TELECENTRIC LENSES

The field of view from most lenses spans outward in a conical shape. However, telecentric lenses are unique in that they gather light only from the area directly in front of them, and therefore have an angular field of view of 0°. Their field of view is equal to that of the diameter of the lens. The advantage of these lenses is their immunity to parallax error – the perceived difference in size of two identical objects that are at different distances from the observer. This is particularly advantageous in machine vision applications when measuring objects that are at different distances from the vision system. Since they will all appear to be the same size on screen, the reliability of the measurements is increased.



LENS COMPATIBILITY

Cameras are often designed to work with a specific lens type to meet certain design criteria, be it for performance, form factor, price, or a number of other application-specific requirements. Lenses have a number of specifications that set them apart, such as the mounting method, back focal distance, and image sensor optical format compatibility.

Lens Mounts

The mounting method, known as the mount type, refers to how the lens interfaces with the camera. The most common mount type is the C-mount lens, which has been in production since 1926. C-mount lenses use a simple screw thread mechanism to affix the lens to the camera, whereas F-mount and EF-mount lenses, used respectively for Nikon and Cannon DSLRs, as well as other cameras with large format sensors, use a turn and lock mechanism, also known as a bayonet style mount.

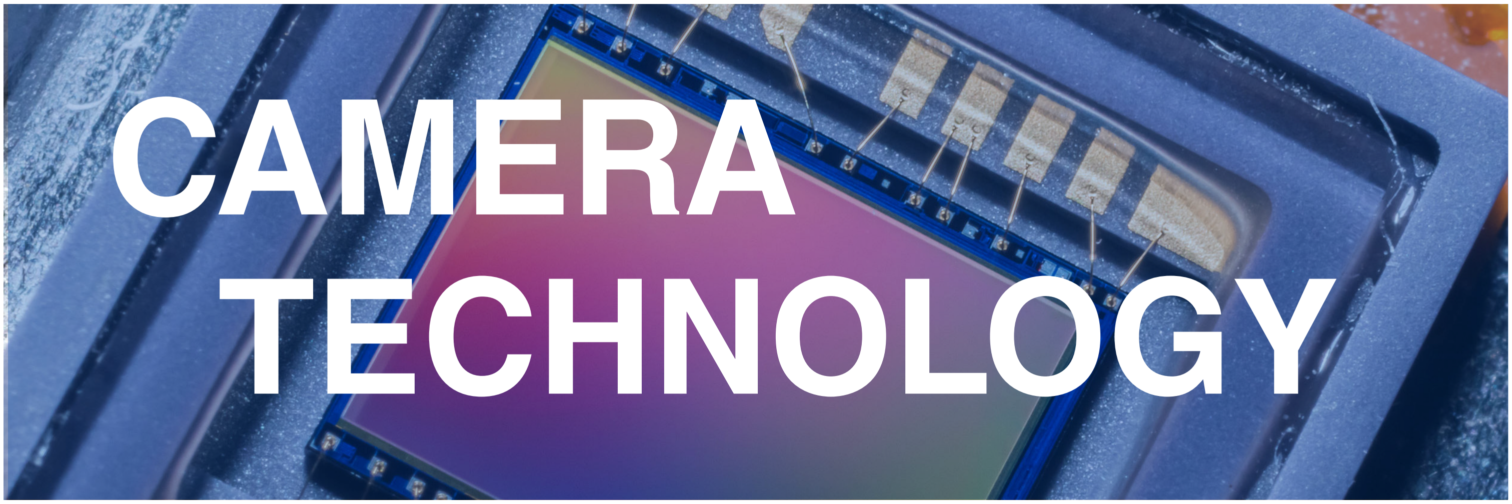
A close cousin to the C-mount lens is the CS-mount lens. The physical size and shape of the screw thread mechanism of these lenses are identical but differ in back flange focal distance – the distance between the rear of the lens and the image sensor. CS-mount lenses have a flange focal distance of 12.562mm, precisely 5mm less than C-mount lenses. Since C-mount lenses require the sensor to be further to focus correctly, a spacer ring can be added to a CS-mount camera to accommodate a C-mount lens.

While it is often best practice to use the intended lens mount style for a given camera, it is possible to use a different format of lens through the use of a lens adaptor if the camera's flange to sensor distance is shorter than the back focal distance of the lens.

Sensor Size

When selecting a lens, the maximum supported sensor size must be matched appropriately to the camera; otherwise a phenomenon known as vignetting could occur. Vignetting is the mechanical clipping of the outer light rays and takes place when the circle of focused light produced by the lens does not cover the entire area of the sensor. This results in the corners of the image being partially shaded or fully black, depending on the severity of the vignetting. Other sources of vignetting can come from using a filter on a wide angle lens, using an adaptor to change the lens' mount style, and using a very wide angle lens, such as a fish eye lens.

Source: Wikipedia



CAMERA TECHNOLOGY

Considering the factors covered in the Lenses & Optics section, the selection of a camera should be made with the lens in mind. The application for the vision system will often dictate many of the camera's requirements, such as resolution, size and weight, color accuracy, and low light performance. These factors are often linked to one another as illustrated in the following section.

IMAGE SENSOR

Most of the camera's specifications stem from the image sensor that it is built around. The sensor will dictate resolution, sensitivity, low light performance, framerate, and dynamic range. Trade-offs between these factors are made during sensor design, and it is important to select a camera and sensor that best suit the application. However it is important to note that two cameras with the same image sensor won't necessarily perform to the same level, as implementation methods and system design used to integrate the sensor will vary.

There are a variety of sensor types and sizes. The first major distinction is CCD and CMOS sensors. CCD technology was the first to hit the digital camera market and is considered more refined. These sensors are typically more expensive but are more sensitive to light and produce more accurate images.

CCD
Charged-Coupled Device – Original and more refined sensor technology offering low noise.

CMOS sensors have been catching up to CCD technology, however, and in certain applications have surpassed CCDs. Some CMOS sensors are now more sensitive than their CCD counterparts and produce less noisy images.

CMOS
Complementary Metal Oxide Semi-conductor – Newer technology offering higher speeds at lower cost.

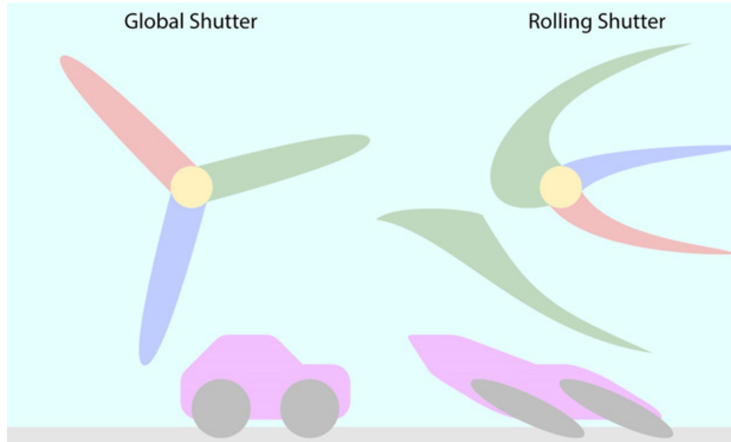
A drawback to CCD sensors is their behavior known as "blooming", where bright spots in an image will saturate the pixels, causing them to "overflow" to adjacent pixels in the row, creating a streak in the image, as seen in the image to the right.

Source: Wikipedia

Image Sensor, Continued...

Sensor Shutter

Another major sensor differentiator is the shutter type – rolling or global. A rolling shutter consists of exposing each line of the sensor one at a time, in rapid succession, whereas global shutters expose all pixels at once. Rolling shutters are subject to blurring or smearing of an object if it is moving at a high rate of speed through the frame during exposure. Global shutters eliminate these artifacts as they freeze moving objects in place by exposing every pixel at the same time. Traditionally, CCD sensors have been the only ones to function with global shutters, leaving rolling shutter functionality to CMOS sensors. However, as CMOS technology begins to surpass CCD, there are now high quality global shutter CMOS sensors available, such as Sony's Pregius sensor.



Source: Wikipedia

Sensor Format

Camera sensors come in different form factors, known as optical formats. Common optical formats are often illustrated in fractions of an inch, including 1/3", 1/2", 2/3", and 1" sensors. However these formats do not relate to the physical sizing of the sensor, rather it is an historical equivalency to cameras using vacuum tubes. The graphic below illustrates the relationship between the optical format of these sensors and their physical dimensions.

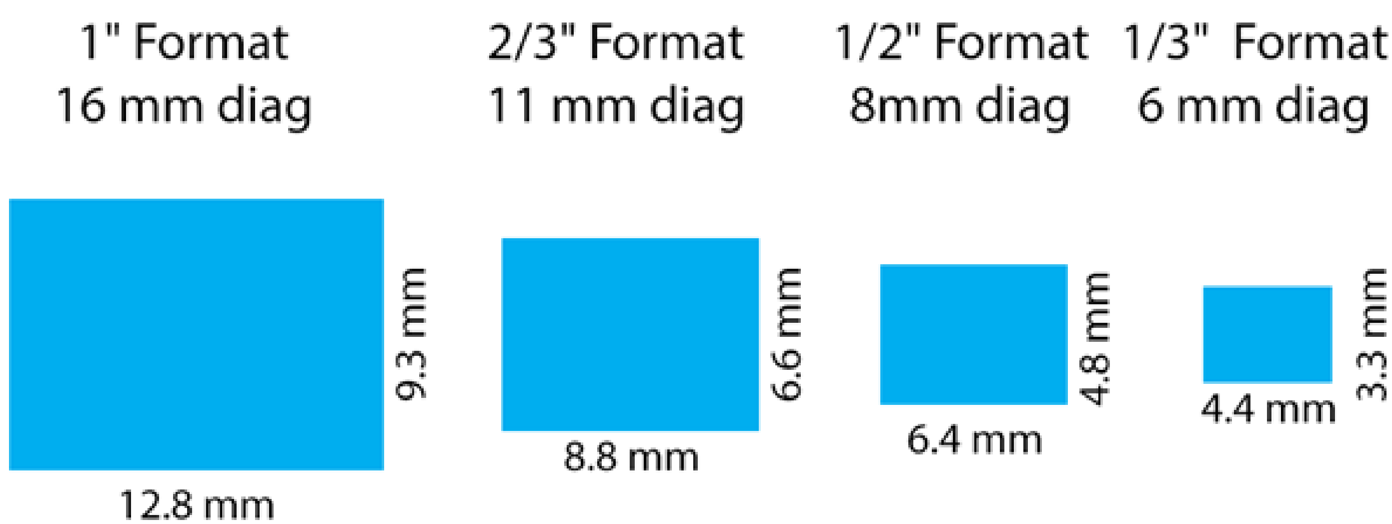
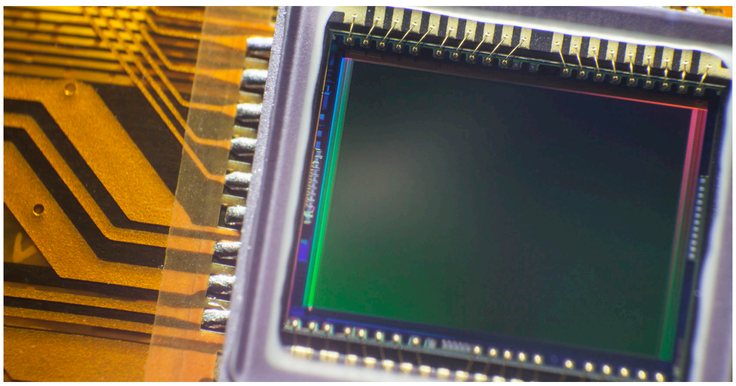


Image Sensor, Continued...

35 mm Sensors

Another common optical format in machine vision systems is full frame sensors, also known as 35mm sensors. Here, 35mm relates to the size of 35mm film, with the sensor having similar dimensions— the horizontal edge spanning roughly 35mm. Unless size is a design constraint, larger sensors are usually favored for vision systems but come with a higher price tag. Larger sensors allow for higher pixel density or larger pixel size.



Pixels

Higher pixel density corresponds to an increase in the camera's resolution, i.e. the camera's ability to resolve fine detail of an object and produce clear and sharp images.

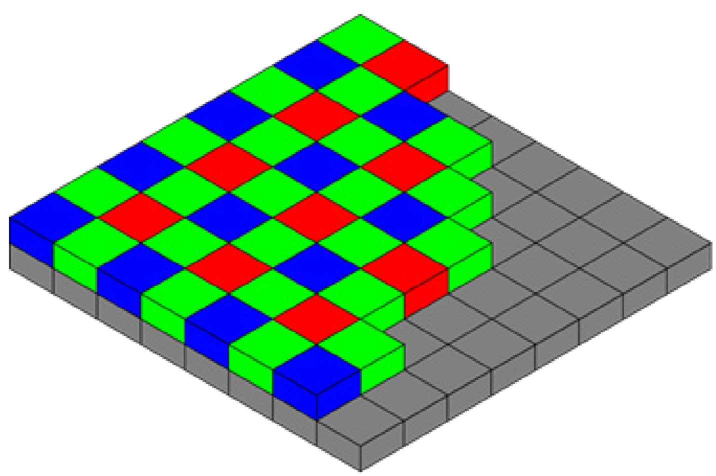
Larger pixels will allow the camera to have a higher sensitivity to light (assuming constant noise) and a higher dynamic range. Since the area of each pixel is increased, more photons can be collected over the surface of each pixel, rendering the camera more sensitive to light. Having larger pixels also means that a higher percentage of the sensor's light sensitive area is used in each pixel, allowing for the conversion of more photons to electrons for each picture element.

A trade-off therefore exists between resolution and sensitivity. Larger pixels will allow the camera to be more light-sensitive whereas smaller pixels over the same area will allow the camera to see finer detail and smaller objects.

Color

The image sensor is also where the distinction between a color and monochrome camera is made. Color image sensors are essentially monochrome sensors with a color filter array (CFA) placed over the imager. The most commonly used CFA is known as the Bayer pattern, where even-numbered rows of pixels alternate between red and green filters, and odd-numbered rows alternate between green and blue. It is up to the camera's demosaicing algorithm to interpolate the missing color data for each pixel from surrounding pixels.

Bayer Pattern:
A color filter array for arranging RGB color filters on a square grid of photosensors to create an accurate color image.



Source: Wikipedia

CAMERA BUILD QUALITY

Selecting a camera with a sensor that meets the application's needs is only part of the process. The camera's overall build quality must also be considered to ensure it is maximizing the potential of the image sensor. A well-built camera should offer robust and reliable operation that produces accurate and clear images without dropping frames.

Quantum Efficiency

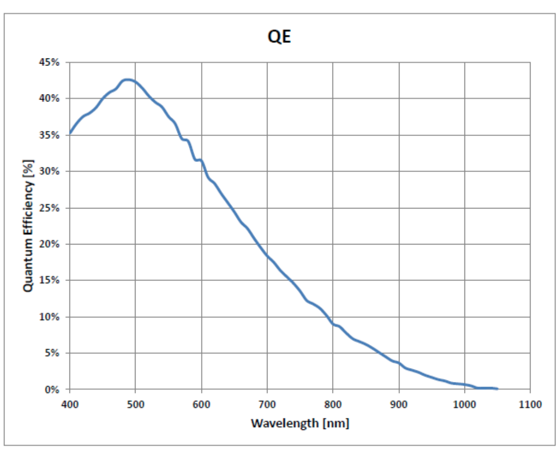
A good metric to compare cameras' sensitivity is their Quantum Efficiency (QE) curves. When comparing these curves, however, it is important to ensure that the camera manufacturer is quoting the *camera's* QE, and not using the QE curve provided by the sensor manufacturer as the camera's final form will result in a drop in quantum efficiency due to the addition of elements in the optical path.

Quantum Efficiency:

The efficiency with which the camera converts the incoming photons of light into electrons on the image sensor.

Quantum efficiency is plotted as a wavelength dependant function, illustrating the percentage incident of photons converted into electrons by the sensor and then read out by the camera. As noted in the below figure, a camera's peak efficiency is typically in the 500nm range, corresponding to green light. Manufacturers often quote peak QE on datasheets to give a general idea of the camera's efficiency, but this value should not be used as the sole point of comparison between cameras. Rather, the entire curve should be compared to ensure that optimum efficiency is attained for the working wavelength(s) to which the application will be subjected.

Monochrome Quantum Efficiency Curve



When comparing the QE curves of color and mono cameras, monochrome cameras are more sensitive to light as no wavelengths are restricted from hitting each pixel. Therefore, if color images are not absolutely essential, it would be advisable to select a camera with a monochrome sensor to take advantage of its higher sensitivity. Furthermore, mono cameras are sensitive to the near infrared (NIR) spectrum as they do not possess an NIR blocking filter that is found in color cameras.

Color cameras have an NIR blocking filter because color pixels remain sensitive to NIR light to varying degrees, and this can cause degradation in color information as NIR light would adversely affect the accuracy of the color channels. As a result, only monochrome cameras are capable of seeing past the visible light spectrum and should be selected for any application requiring NIR imaging.

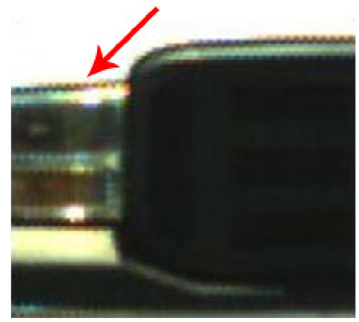
Camera Build Quality, Continued...

Color Reproduction

Another testament to the camera's build quality is its ability to accurately reproduce color with minimal artefacts. A color camera must interpolate missing color data from two color channels with the help of surrounding pixels through a process called demosaicing. Different levels of thoroughness can typically be selected at a cost of computing cycles based on the selected demosaicing algorithm. Less accurate algorithms will introduce image artefacts such as false colors, moiré effect, and zippering as well as sharp changes in contrast, such as dark lines on a white background.

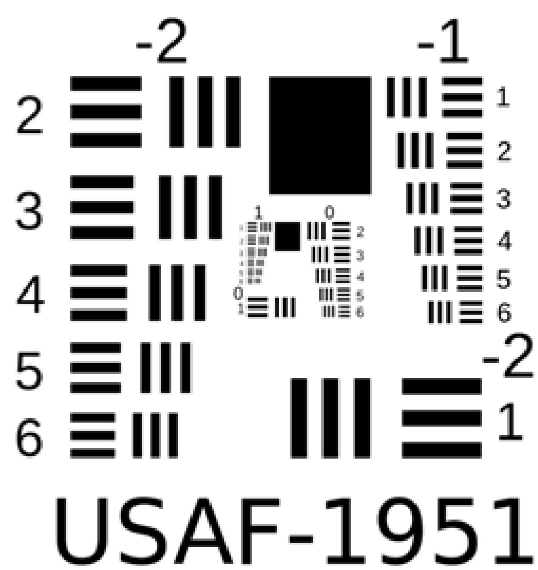
False Color

Moiré Effect



Zippering

When selecting a camera, it is best to evaluate it using a number of targets designed to highlight these artefacts and ensure proper image reproduction. Targets with varying degrees of high frequency patterns, such as the 1951 USAF resolution test chart, can help to highlight instances of false color, whereas ColorChecker targets can help calibrate the camera and ensure accurate color reproduction.



Source: Wikipedia

Source: Wikipedia

It is important to note that color verification targets should be purchased from a supplier and not simply printed as each printer's color accuracy will vary and cannot print at a high enough resolution.

Camera Build Quality, Continued...

Camera Framerate

The camera's maximum frame rate is another key indicator of its design quality. Some cameras will start to drop frames once the frame rate is set too high and they are unable to deal with the increased data payload. In other cases, it is possible to overclock CCDs to achieve higher frame rates, but this can affect the performance of the camera. Well-built cameras will be able to sustain these accelerated rates without an increase of noise or dropped frames. Once again, the cameras should be tested and compared as some manufacturers will list the sensor's maximum frame rate as their own.

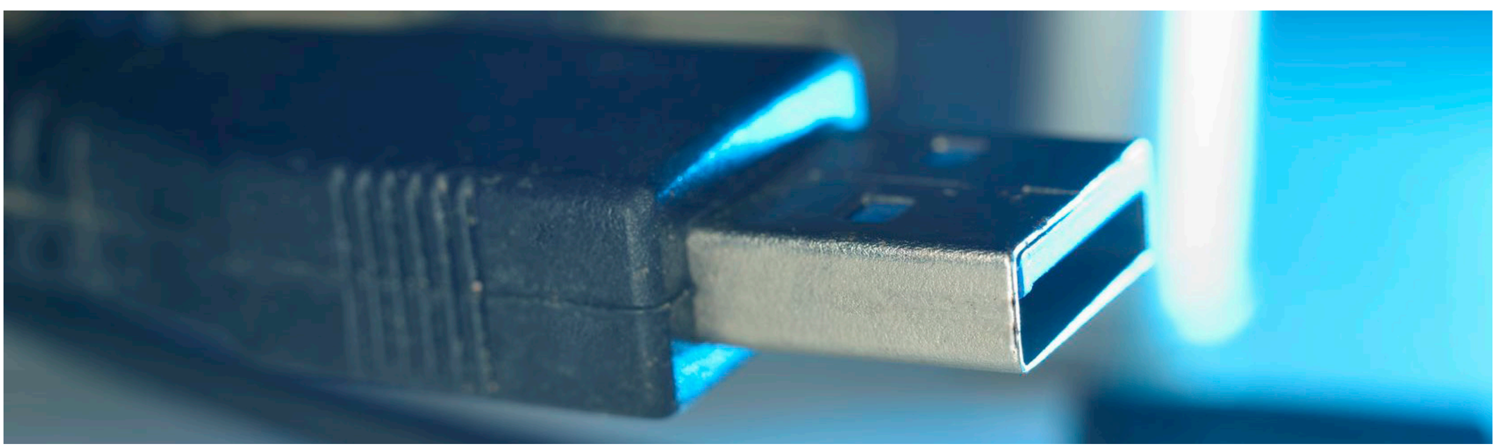
GPIO & Reliability

For a camera to communicate with the outside world, it will typically come with a number of general purpose input and output (GPIO) channels. Not only is it important to meet the application's requirements in terms of quantity of GPIOs, but in determinism and reliability as well.

The selection of an industrial-grade camera over a commercial-grade point-and-shoot camera or DSLR for the application will result in a more reliable communication process. A commercial-grade camera will often have a significant lag between the trigger signal and the shutter actuation, which can cause problems when integrated into an application where an event occurs for a short period of time.

To further complicate this scenario, the trigger delay of a commercial-grade camera also comes with a relatively high level of variance, preventing the usage of a system-wide delay to compensate for the camera's lag. Industrial-grade cameras are not only designed to run 24 hours a day, but also to reliably and deterministically trigger as part of a complete imaging system. They are also designed to trigger external events, such as camera flashes or other hardware triggerable events that are often integral within an application.

USB 3.0 INTERFACE



Considering the large number of interface options available, this paper will exclusively discuss USB 3.0 as it is the easiest interface to use for machine vision applications due to its plug-and-play nature and since it does not require the use of a frame grabber. USB is widely available as a standard computing interface and easily understood by vision professionals and consumers alike.

USB 3.0 Interface, Continued...

Speed & Distance

USB 3.0 can reach bus speeds of up to 5 Gbps. After taking overhead into account, the interface allows for transfer speeds of roughly 400 MBps of image throughput. With the standardized mechanical configuration of the new USB cables, USB 3.0 cables can also support the newly developed USB 3.1 protocol capable of bus speeds of 10 Gbps and throughput of well over double that of USB 3.0. This is due to the reduction of encoding overhead from 20% with USB 3.0 to 3%, as it uses a 128b/132b encoding scheme. This means that for every 128 bits of data needing to be sent, 132 bits of data are sent to make the transmission more robust. Using Direct Memory Access (DMA), USB 3.0 and USB 3.1 benefit from CPU offloading, requiring far less processing resources from the host CPU and allowing it to perform image post-processing, image analysis or other unrelated tasks.

A common misconception for USB 3.0 applications is that the maximum permissible cable length is rather short and cannot surpass 5m. As this is true for passive USB cables made of copper, there exist solutions that greatly extend the range of USB 3.0.

There are two main methods that can be used to extend the range of USB3. The first is the use of an active cable, where embedded electronics within the cable ensure signal integrity at lengths of up to 20m. An active and passive cable can also be combined to further extend the transmission range. The second option to consider is the use of a fiber optic extender cable, which can achieve a transmission distance of up to 100m. This second option, however, is power limited as the fiber optic cable cannot carry power. It will have to be injected at the far end to power the camera.

Combinations of these extension methods can be coupled with a powered USB 3.0 hub. Active and passive cables can be connected to a powered hub to deliver connectivity and power to the cameras. The hub can be connected to the far end computing host via fiber optic extender, aggregating the data from all the cameras on the hub onto a single connection. This translates to each camera receiving 1/N of the total available bandwidth of the fiber connection to the host computer, where N is the number of cameras connected to the hub.

The build quality of the USB cables and hubs should not be overlooked, as lower quality cables will reduce the overall performance of the system. Locking cables should be used when available to ensure inadvertent camera disconnection does not occur. The camera manufacturer's recommendations should be followed when selecting cabling for any application.

USB3 Vision

USB3 VISION

Released in January 2013, USB3 Vision is the newest machine vision standard. It was created explicitly for the machine vision industry as it brought together the expertise of many companies to create a standard that is plug-and-play, has a high level of performance, and is compatible with all newly manufactured computing systems.

USB3 Vision was created with the GenICam (Generic Interface for Cameras) standard in mind and allows cameras using the interface to be seamlessly integrated into a system using this standard.

This off-the-shelf hardware approach does not require specialized cables or frame grabbers and leverages hardware DMA to transfer images from the camera's hardware to user buffers. Coupled with the new encoding scheme of USB3.1, USB3 Vision is the fastest transfer protocol for a camera that does not require a frame grabber.

CONCLUSION

Although this is not an exclusive list of considerations for choosing a camera and lens for your vision system, this overview of high level requirements is a first step in helping you identify the correct set up.

Lumenera understands your imaging needs and we're here to help you get the most out of your camera whatever the imaging application. All Lumenera cameras come with a 4 year warranty and are supported by an experienced team of technical support and imaging experts.

ABOUT LUMENERA CORPORATION

Lumenera Corporation, a division of Roper Technologies, headquartered in Ottawa, Canada, is a leading developer and manufacturer of high performance digital cameras and custom imaging solutions. Lumenera cameras are used worldwide in a diverse range of industrial, scientific and security applications.

As a global market leader Lumenera provides an extensive range of high quality digital cameras with unique combinations of speed, resolution and sensitivity to satisfy the demands of today's imaging applications. Lumenera also offers custom design services to OEM partners requiring specialized hardware and software features.

Core competencies include digital bus technologies such as USB 3.0, USB 2.0, Ethernet, HDMI and Gigabit Ethernet (GigE) as well as a complete command of digital imaging hardware and software built around CMOS and CCD based imagers. Our diversity provides our customers with the benefits of superior price-to-performance ratios and faster time-to-market.

Lumenera Corporation
7 Capella Court
Ottawa, ON
Canada, K2E 8A7

613-736-4077
info@lumenera.com
www.lumenera.com