Selecting the Right Lens for Your Machine Vision Camera

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Even with the challenges associated with today's technological advances in digital imaging, selecting the proper lens for your machine vision application need not be difficult if approached in a systematic manner. Here are three steps with brief explanations about the methodology.

Why it's Important

Early machine vision systems were a big, costly and low resolution. The fledgling machine vision industry relied on cameras and lenses developed for security applications. The digital revolution introduced higher resolution image sensors, but the lens quality was still adequate for most early digital cameras. With the introduction of Megapixel sensors, machine vision application engineers began to experience the limitations of security-type lenses. Today, demand for higher-quality optics continues to increase as pixel size decreases and image sensor sizes increase. Machine vision applications present a unique set of imaging challenges. This article outlines a systematic approach to lens selection along with some background rationale.

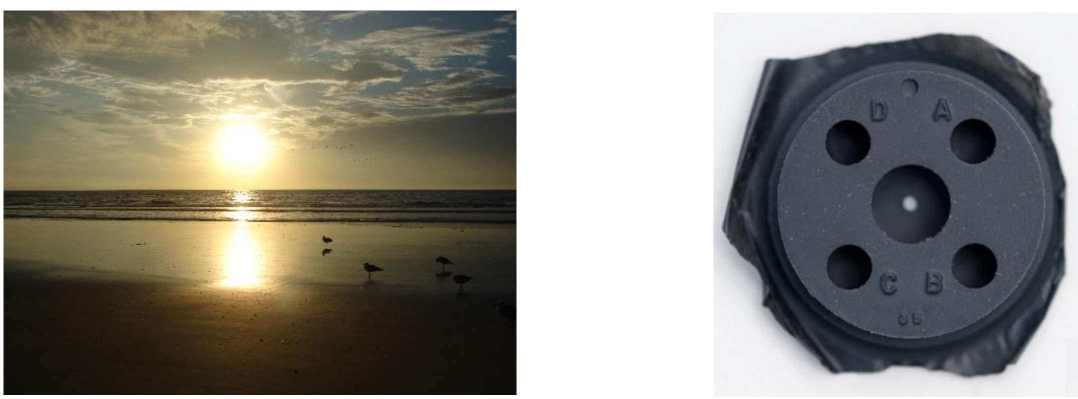

Figure 1: Sunrise on the Beach and a Flashy Rubber Part

Frequently the question is asked, "I see beautiful, good-quality images on my cell phone. Why must I spend hundreds, sometimes thousands, of dollars for an inspection camera system?" The simple answer is that computers are not quite as smart as humans. The human brain does a fantastic job "filling in the blanks" of information in a scene. In addition, manufacturers of cell phones and, for that matter, consumer digital cameras, have gotten very good at deploying software that enhances images for human viewing. We see stunning still and video images of people, animals, plants and natural landscapes- images so true to life as to be almost touchable. Machine vision is not like that.

Rather than aesthetically pleasing pictures for human enjoyment, machine vision images are designed to use raw video for computer analysis. Information about each pixel and its relationship to its neighbors is analyzed to yield data for measurement, pattern detection, geometric relationships and a host of other low-level data extractions. The purity of this data directly affects the accuracy of the information to be extracted. And the purity of the image data is a function of the camera image sensor that captures photons from the scene and the lens through which those photons pass.

Where Do I Start?

When designing a machine vision system, the first step is knowing the accuracy requirement of the application. This will drive the resolution requirement for the image sensor, which will then dictate the lens selection criteria.

1. Application Accuracy and Image Sensor Resolution

System resolution requirements will vary by application. Surface appearance, lighting, software algorithms to be employed: these all affect the measurement accuracy and required system resolution. Spatial constraints will dictate acceptable working distances and part geometry the Field of View. For purposes of this discussion, an accuracy of 0.02mm, a Working Distance of 100mm and a FOV of 10mm is assumed.

2. Digital Camera Sensor Resolution

A digital camera transforms light (photons) into electrical information. It consists of an image sensor and supporting electronics to transmit information to a computer. The image sensor is an array of photosensitive elements or pixels. An individual pixel may vary in size from 1 micron to several microns and is usually square. Each pixel senses the amount of light that is projected onto it over a given amount of time, after which that number is extracted by the electronics. Each time segment is a scan. The number of photons in each scan yields the intensity of the light, measured in shades of gray (0 = black; 255 = white). Color cameras use the same method, except that color filters are added to the pixels. Pixel arrays vary in size from a few hundred to several million (Megapixels) and conform to a standard rectangular format.

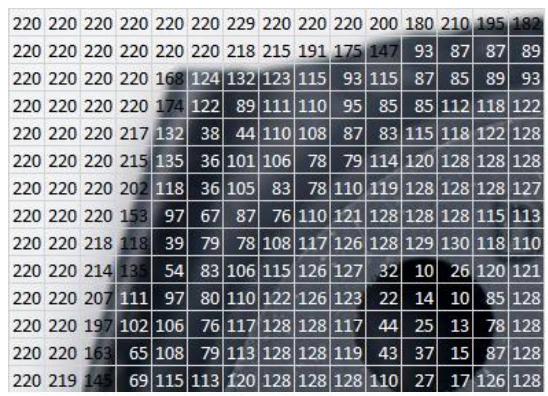

Figure 2: Pixel Matrix

Selecting the proper sensor resolution is a matter of calculating the number of pixels required to accurately measure the area of the part to be inspected. For example, assuming the shorter axis to be inspected (Field of View) is 20mm and the required measurement accuracy is 0.02mm, the required number of pixels is 2000, per the following equation:

Number of pixels		=	Field Of View (mm)	
			Accuracy (mm/pixel)/2	
2000	pixels	=	20	(mm)
			0.02	(mm/pixel)

This calculation assumes the number of pixels in the horizontal axis and that two pixels are required to determine a lighting transition. Please note that these are “raw” measurements and do not account for any statistical advantages that may be achieved with software.

Research on cameras finds several image sensors whose cameras would meet this specification. Here are two:

sensor	sensor size	MP	resolution	pixel size in uM
Anafocus Lince 5M	1"	5.20	2560 x 2048	5 x 5
Sony IMX250	2/3"	5.04	2456 x 2054	3.45 x 3.45

Note that one sensor size (format) is 1” with 5.5µm pixels and the other is a 2/3” format sensor with 3.45µm pixels. BOTH are 5 MP sensors with about 2000 pixels available in their vertical axis. Before addressing the issue of lens resolution, the focal length corresponding to the sensor format must be calculated.

Digital Camera Sensor Optical Format

An excellent explanation of sensor format may be found at Wikipedia (Image Sensor Format, 2017). Listed below are some of the more common sensor formats used in machine vision. The optical format is equal to the sensor diagonal measurement multiplied by 3/2 and expressed in inches, a holdover from the early television days where the overall target was smaller than the overall tube diameter. The table below lists some common sensor formats and their parameters.

Type (inches)	Diagonal (mm)	Width (mm)	Height (mm)	Area (mm
4/3	21.6	17.3	13	225
2/3	11	8.8	6.6	58.1
1/3	6	4.8	3.6	17.3
1/2.5	7.18	5.76	4.29	24.7
1/2	8	6.4	4.8	30.7
1/1.8	8.93	7.18	5.32	38.2
1	15.86	13.2	8.8	116

A useful calculation for optical format if the pixel size and array parameters are known is:

Optical Format = (p*(SQRT w sqr + h sqr)/16000

(Optical Format, 2017)

Lens to Sensor: Image Circle

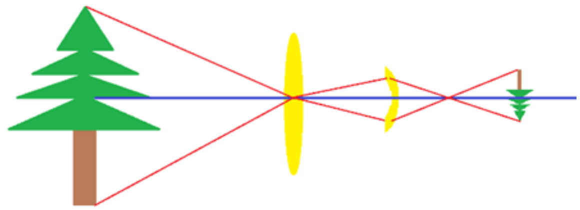

Figure 3: Lens Stages and Refraction

The lens projects photons onto the image sensor. It usually consists of a series of stages of light transmissive material through which the photons from the scene are refracted (change direction) for projection onto the image sensor chip. Each refraction stage introduces distortion; succeeding stages are designed to compensate for the distortion of their predecessors, with the least distortion occurring nearest the optical axis (center of the image circle).

Because the lens is a cylinder the resultant projection onto the rectangular sensor is circular; its diameter may be found in the lens specification. Customary practice is to select an image circle greater than or equal to the larger (horizontal) axis of the sensor. Supported sensor formats will be listed in the lens specification (e.g. ½" lens format for either a ½" or 1/3" sensor; 2/3" sensor for 2/3" or ½" sensor, etc.). Selecting a lens format that is smaller than that of the sensor results in unused sensor pixels, increases distortion and vignetting. Since distortion increases towards the periphery of the lens, it may be preferable for some applications to use a slightly larger format lens, provided the lens resolution is not compromised.

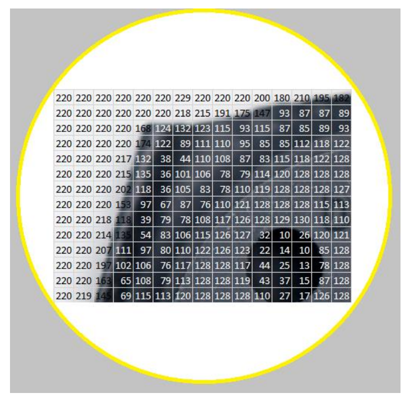

Figure 4: Image Circle vs. Sensor Chip

Working Distance, Field of View, Focal Length

The equation to calculate Focal Length is given as follows:

Focal Length (mm) = Lens Format (in)* Distance to Object (ft.)/FOV horizontal (ft.)

There are also a number of calculators available online.

Given the selected lens formats from above of 1" and 2/3", a Working Distance of 100mm and the previous FOV of 20mm, the respective Focal Lengths are 66mm and 44mm.

Perusing the lens catalog for a 5MB lens, 50mm lenses are found in each format. The WD will need to be adjusted slightly to accommodate these standard lenses.

The next step is to determine which of the selected lenses will accommodate our required resolution.

3. Lens Resolution

The ability of a lens to resolve to a certain clarity is determined by the lens material, the quality of the manufacture, number of stages, and the laws of physics. Unlike the pixel matrix, however, lens resolution is not discretely digital; it is analog and affected by many variables such as location within the lens, light intensity, contrast, and wavelength.

Line Pairs per millimeter

Lens resolution is commonly expressed in line pairs per millimeter (lp/mm), the measurement of which is performed at the factory and becomes part of the lens' specification. The term describes the ability to discern the border (edge) between two lines, one black and one white, in an image produced by the lens. More line pairs per unit measure allow more detail. Discrimination between black and white lines, however, also depends on contrast: the greater the contrast the easier it is to determine a black/ white boundary. The more line pairs per millimeter, the more contrast is required to discern the boundary difference. Line pairs per millimeter, therefore, are meaningful only when expressed at a given contrast level. An excellent explanation of lens resolution may be found at Edmund Optics (Resolution, 2017).

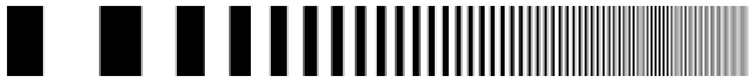

Figure 4: Line Pairs

One analogy for a pixel is that of a photon bucket. Smaller buckets result in more detail at the lower light: a small bucket mouth means that the photons come from a straighter angle and a smaller bucket fills up more quickly. Larger buckets accept photons from wider angles and take more time to be filled.

An analogy for a lens might be that of a screen. Photons travel in a straight line until refracted, whereupon the direction of the straight line is changed. A lens with a higher lp/mm rating may be compared to a fine screen. It will allow smaller photon lines to pass through. The angle at which the photon line strikes the pixel will be smaller, resulting in greater clarity.

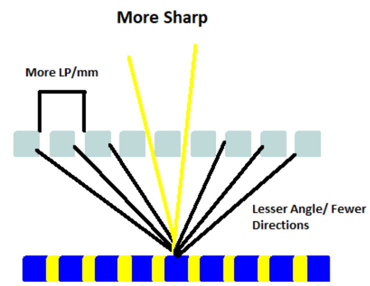

Figure 5: Light from Fewer and Lesser Angles

On the other hand, a lower-quality lens rated at fewer lp/mm will allow wider photon lines to pass through, resulting in less detail.

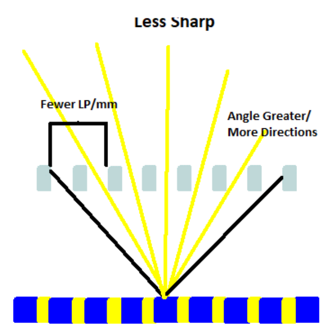

Figure 6: Light from More and Greater Angles

It is the combined resolution of both components, the lens, and the sensor, that determines the final resolution of the optical delivery system (ODS). If a high-resolution lens is coupled with a low-resolution sensor, then the sensor is the constraining component of the optical delivery system. Likewise, if a low-resolution lens is coupled with a high-resolution image sensor, then the ODS performance will be limited by the lens. Matching the two results in optimal system performance.

The formula to select the lens resolution for a given pixel size is given as:

Lens Resolution		=	1000 µm/mm		
			2 x	pixel size (µm)	
			1000	(µm/mm)	
90.91	lp/mm	=	5.5	µm	
Lens to Sensor Resolution		=	lp/mm	x	mm/pixel
1.82	lp/pixel	=	90.91	x	0.02

Calculating for a 5.5µm pixel yields 90.91 lp/mm and at 0.02mm/ pixel, there is 1.82 lp/ pixel.

Lens Resolution		=	1000 µm/mm		
			2 x	pixel size (µm)	
			1000	(µm/mm)	
144.93	lp/mm	=	3.45	µm	
Lens to Sensor Resolution		=	lp/mm	x	mm/pixel
2.90	lp/pixel	=	144.93	x	0.02

From the above, a 5.5µm pixel requires a lens with 90.91 lp/mm and a 3.45µm pixel requires 144.93 lp/mm.

Some lens manufacturers provide the optical properties of their products, while others consider this intellectual property. If published lp/mm is available it is important that the contrast level for that value is also specified. Note that, for machine vision applications, >= 30% contrast is the suggested value at which to select lp/mm.

If the resolution data is not published, some manufacturers will fulfill special requests after submission of contact information and application specifics. This data will often be in the form of an MTF chart.

MTF

The most common lens resolution data is found on the MTF (modulation transfer function) chart. MTF is a complex topic with many good discussions to be found on the web, many of which relate to the study of optics and photography. Reading relevant to machine vision may be found at Wikipedia (Optical Transfer Function, 2017) and Edmund Optics (Modulation Transfer Function and MTF Curves, 2017). For these applications, an MTF chart that plots contrast and lP/mm is most useful.

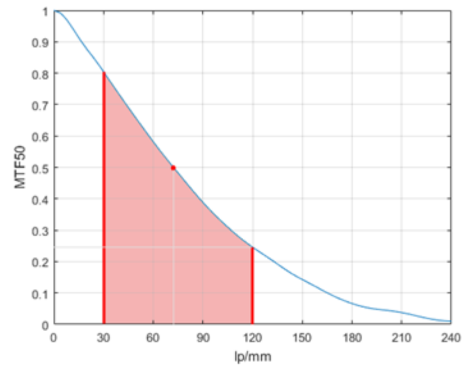

Figure 5: MTF

The MTF chart in Figure 5 depicts how the contrast between line pairs degrades as the distance between the lines decreases (number of line pairs per millimeter increases). High-quality lenses preserve greater contrast at greater lp/mm, while with the low-quality lens is unable to support differentiation between line pairs at higher spatial frequencies. It is important to obtain the MTF chart for a resolution-critical machine vision application.

Putting it all Together

Given the application accuracy requirements:

1. Determine sensor resolution.
2. Determine lens resolution and sensor format.
3. Obtain lens focal length for the sensor format, field of view and working distance, then select the appropriate optical resolution.

Once appropriate lens options have been determined, it becomes a matter of cost/ benefit. An online search for a 50mm lens to accommodate either sensor format with 200 lp/mm may be obtained for approximately $1300; a lens with 120 lp/mm costs around $600.

References

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