LUMENERA **WHITE PAPER SERIES**

Getting it Right: Selecting a Lens for a Vision System

A Comprehensive Technical Guide to Selecting a Lens to Meet the Unique Requirements of Your Vision System

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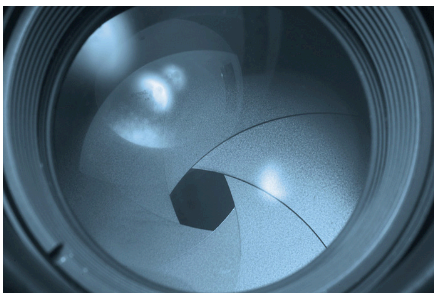
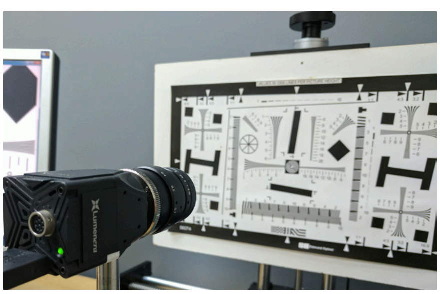




WHAT'S INSIDE

Introduction

When building a vision system, the two main components – the camera and the lens – must be selected to work together as a pair. They must work together to correctly resolve and transmit the required visual information of a scene. The main question to ask when selecting a camera and a lens is: What is the smallest detail in the scene that needs to be resolved? The answer to this question might not be obvious at first and will likely generate a number of subsequent questions. Alternatively, the answer might be the starting point (e.g. reading licence plates on a car travelling on a toll road, or inspecting bar codes on packaging before a product is placed inside). Again, this will likely generate more questions.

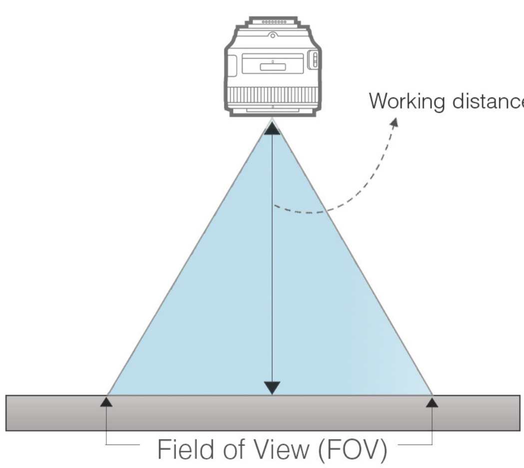
Remember, each vision system and application is different and there is no absolute “best” answer when it comes to building a system. This paper will take a functional approach to selecting a lens and matching it to a camera, but the real value is learning the steps to uncovering the very specific answers to questions on selecting the right lens to work on your vision system camera. The lens or camera manufacturers being considered should ultimately be responsible for addressing specific design questions.

Focal Length

The easiest place to start is system working distance (distance between the front of the lens and the scene). Since there are often stringent restrictions on where the camera system can be placed (e.g. Close to an assembly line or above a highway) the lens focal length can be determined by knowing the working distance and required field of view. For a mathematical approach to determining the focal length, use the following formula where d is the horizontal (or vertical) dimension of the image sensor, WD is the working distance, FoV is the horizontal (or vertical) field of view, and f is the focal length of the lens.

Working Distance:
Distance between the front of the lens and the scene:

$$\frac{d \times WD}{FoV} = f$$



For example, if a 20 vertical centimetres (200 mm) view of a scene is needed and the camera, using an image sensor measuring 8.7792 mm high, needs to be 37 cm (370 mm) away from the surface to be imaged, these values would then be substituted into the formula as follows:

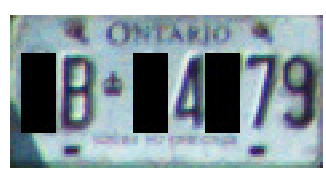
$$\frac{8.7792 \times 370}{200} = 16.24\ mm$$

The result shows a need for a lens with a 16 mm focal length in order to correctly image the scene.

Alternatively, if the camera you will use in your system has already been selected, consider purchasing an inexpensive (lower quality) varifocal lens to experimentally determine a suitable focal length for the application. Ideally, select a varifocal lens that has a number of focal lengths physically written on the lens to avoid guesswork.

Camera Resolution

Once the required focal length for the system has been determined, next is determining the required resolution of the camera. The result will determine how each pixel falls onto the field of view and the area that each one will cover. Returning to the example of a camera scanning vehicle license plates, in order to ensure that a license plate is resolvable by machine vision software, it would need to be covered by roughly 100 pixels across.



Partially Censored License Plate Measuring 117 Pixels Across Taken With the Lumenera Lt29059 Camera

Again, the camera's pixel projection onto the scene can be worked out mathematically. With the known physical dimensions of the field of view and the various sensor sizes that are being considered, a ratio between the two can be established. Then use the sensor's pixel density to calculate the area covered by each pixel in the scene.

A great way to visualize this is to think of a projector. The farther away it is from a screen, the larger the projected image will be (with the pixel size increasing in relation to the distance). To achieve a sharper image, increase the pixel density. In this case, it is the reverse. Figure out how the camera would see each part of the field of view and select its resolution accordingly.

The mathematical formula is quite similar to the one previously used. Since the focal length and working distance have already been determined, next is trying to map a dimension in object space to a dimension on the image sensor. The formula becomes:

$$\frac{f \times y}{WD} = y'$$

f and WD remain the focal length of the lens and the working distance, respectively, and y and y' are the linear dimension in the object space and image space, respectively. Substituting into the formula the the previously calculated numbers (working distance of 37 cm and our lens of 16 mm), results in how much space 1 cm (10 mm) will physically occupy on the sensor:

$$\frac{16 \times 10}{370} = 0.4324\ mm$$

From this, the result of 0.4324 mm or 432.4 microns are obtained, meaning an object measuring 1 cm in length will occupy almost half of a millimetre on the image sensor.

It may be tempting to use that same inexpensive varifocal lens to experimentally determine the required sensor size and pixel count, but this should be avoided as the system's resolution is determined by two factors.

The first and most obvious source is the camera's resolution given by the pixel count in megapixels. More megapixels equates to a higher resolution camera which allows you to see more detail within your field of view. The second lesser known source is the lens design. Therefore, using a lower quality lens could lead you to choosing a higher resolution camera to try and compensate for the poor lens design.

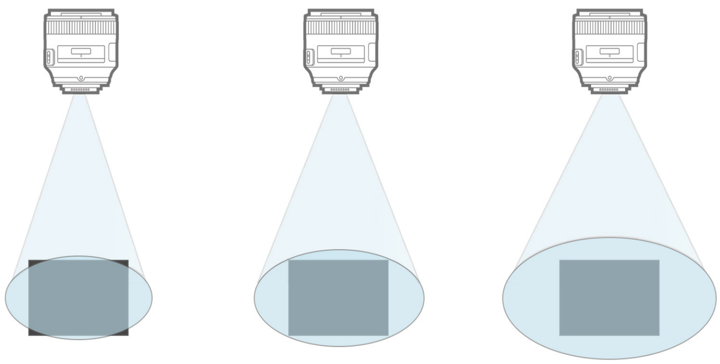
Sensor Size Compatibility

Lenses are designed for specific sensor and pixel sizes. First, select a lens whose image circle fully covers the camera sensor. Otherwise, a phenomenon known as vignetting occurs. Vignetting is when the image disc created by the lens does not reach all four corners of the sensor and results in shading in the corners of the images (See below).

Sensor Size Compatibility:
The match between a lens image circle and sensor size.

Source: Wikipedia

Matching a lens to the sensor ensures that there is no vignetting present in the image. Lens manufacturers typically classify the lenses to match with common sensor sizes including 1/3", 1/2", 2/3", and 1". When selecting a lens to pair with a camera, preferably select one that matches the specific camera being used. If a lens is selected with an image circle that is much larger than the sensor size, magnification, not vignetting, will occur. The graphic below demonstrates how the image circle appears on the camera sensor when the circle is: (1) smaller than the sensor, (2) matched to the sensor, and (3) bigger than the sensor.



Once a camera is selected, shop for lenses that conform to its sensor size to fully benefit from the performance of the lens.

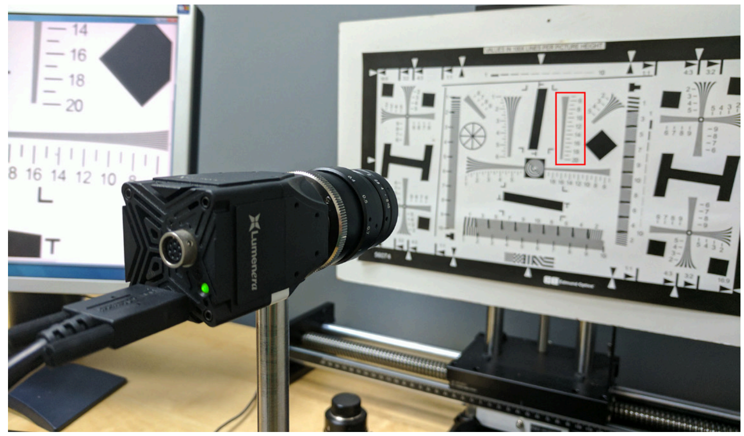
Resolution Compatibility

Lenses are designed to work with image sensors up to a specific resolution or with pixels no smaller than a specific size. After this point, the lens becomes much less effective at resolving the detail that the camera should be able to resolve.

Resolution Compatibility:

The match between a lens and sensor resolution or pixel size.

The following practical experiment uses a resolution chart from Edmund Optics, three different cameras from Lumenera Corporation, and two lenses from Kowa. Here, the horizontal field of view needed to be 20 cm to correctly use the resolution chart. Since 16 mm lenses were used, the math from the previous examples applies to this practical experiment. It is important to note that the working distance for each camera varied slightly as the aspect ratio of each sensor was slightly different, thereby impacting the horizontal dimension of the sensor.



Practical Experimentent Setup

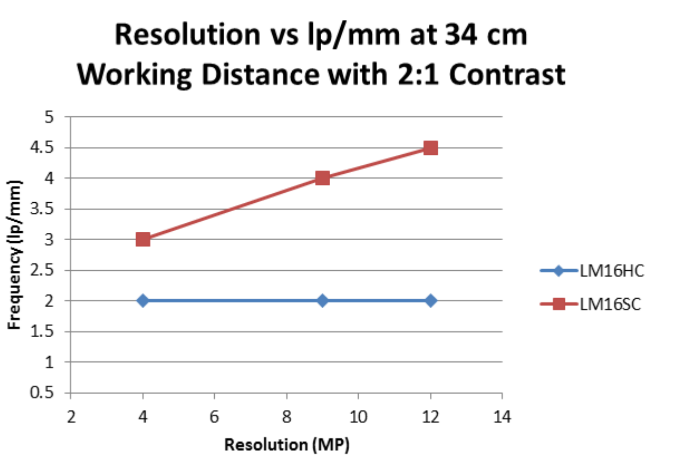
The targeted the vertical resolution bar highlighted in red in the above image and calculated at which point each lens and camera pairing achieved a contrast level of 2:1. This was done in ImageJ by measuring a linear cross section of the vertical resolution chart to determine the maximum and minimum pixel values for each of the nine line pairs. The values were then averaged to calculate the contrast ratio. The linear cross section tool measured increasing line pair density until a 2:1 contrast ratio was achieved.

The cameras used for this experiment were the Lumenera Lt425C, Lt965RC, and Lt1265RC. Below is a table outlining their relevant specifications.

	Lumenera Lt425C	Lumenera Lt965RC	Lumenera Lt1265RC
Resolution	4MP (2048 x 2048)	9MP (3376 x 2704)	12MP (4240 x 2832)
Sensor Size	1”	1”	1”
Pixel Size	5.5 x 5.5 µm	3.69 x 3.69 µm	3.1 x 3.1 µm

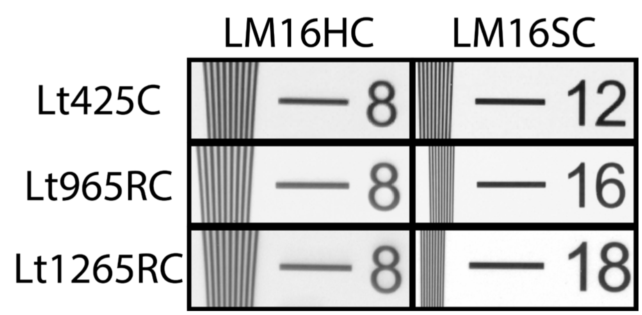
For this experiment, color cameras were used and set to grayscale mode to eliminate false color artefacts. However, in a production environment, monochrome cameras would yield better contrast since there is no interpolation of data which takes place with color cameras because of the use of the Bayer filter pattern. Since both lenses in the experiment were compared with color cameras, the results remain valid.

The lenses used were the Kowa LM16HC and LM16SC. The largest aperture for each lens was used in each case to minimize the amount of diffraction and not impact the apparent resolution of the lens. For the LM16HC, the minimum possible aperture was f/1.4 and for the LM16SC, it was f/1.8. These lenses were selected for this exercise because they are designed to work with 1" sensors. The LM16HC (MSRP: $550 US) is rated for use in cameras with pixels no smaller than 5 µm. When used with a one inch sensor, this equates to a resolution of roughly four megapixels. As resolution increases and consequently pixel size decreases, the visual information that should only occupy a few pixels starts to bleed over to neighboring pixels and results in poor contrast where the lines are tightly spaced. The LM16SC (MSRP: $920 US) is rated for use in cameras with pixels no smaller than 3 µm. For a 1" sensor, this translates to over 12 megapixels.



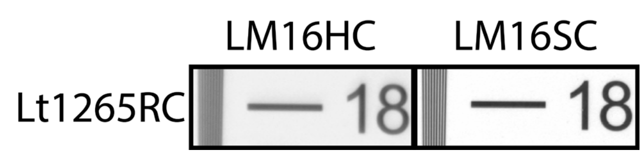
The results of our experiment confirm this behavior. The graph above shows that LM16HC is unable to achieve higher contrast with more resolution, whereas the LM16SC is able to increase the image contrast as pixel density increases.

The following image highlights where each datapoint above was calculated. The number next to the lines represents the number of line pairs times 50 divided by the image height, which in this case was 20 cm. The conversion to line pairs per milimeter for the below image means dividing by 4.



Line Pairs per Millimeter at a 2:1 Contrast Ratio for Each Camera-Lens Pairing

By taking a close look at the Lt1265RC (12 Mega pixel sensor) for both lenses at 4.5 lp/mm, it is easy to see that the LM16SC lens is the clear winner, with the LM16HC lens unable to make out any detail among the line pairs.



Resolution Chart at 4.5 lp/mm for the Lumenera Lt1265RC Camera

Here, the LM16HC is unable to resolve the lines that are spaced closely together and the resulting image is a blurry gray line.

It is important to note that when dealing with resolution at these levels, the camera's focus can drastically vary the contrast in the captured image. An extremely precise level of focus is required to attain the system's maximum resolution. For this experiment, the lenses were focused as sharply as possible for each captured image.

Other Considerations

Lighting

If after a selection process, a wide range of lenses still remains, an additional consideration would be the maximum aperture. Maximum aperture is the largest possible opening of the lens' iris. It allows the most amount of light to be transmitted through the lens to the image sensor. If the scene is not brightly lit, additional lighting may be required. However, some cameras are sensitive enough to work in low light conditions. Different lenses also have different maximum apertures and selecting a lens with a larger aperture increases the amount of light passed along to the sensor.

Maximun Aperature:
Largest possible opening of the lens' iris.

In the previous examples, the lenses had differing maximum apertures, with the LM16HC opening to f/1.4 and the LM16SC opening to only f/1.8. This means that the LM16HC allows 1.5 times more light to pass through to the sensor than the LM16SC. So, if the application does not require resolution past 4 megapixels, a benefit is the higher quantity of light transmitted through the LM16HC possibly reducing or even removing the requirement for supplemental light.

Use of Infrared and Visible Spectrum

If the application requires the use of a wider spectrum of light (e.g. Hyperspectral imaging with a single camera) an IR-corrected lens will be required. This is due to the physical property of light known as dispersion. Dispersion is white light being separated into its component colors as it passes through denser materials – in this case, the glass elements of the lens.

Dispersion:
White light separated into component colors as it passes through denser material.

Lens manufacturers compensate for dispersion within the visible spectrum for all lenses, but will focus less on the dispersion of IR light unless the lens is specifically designed for this. If a lens is not designed for visible and IR light, it will have two focal points for each group of wavelengths. This means that if the system were to alternate between visible and IR light, the focus of the lens would need to be changed even though the camera and the target have not moved. Using all of this light simultaneously would cause some subtle blurring in the image as light from one of the two groups of wavelengths would be out of focus. Using an IR corrected lens would eliminate this as the dispersion of IR light is also taken into account and realigned onto the focal point of the lens.

Iris Control

In cases where the illumination of the scene is variable (e.g. outdoor applications), the preferred method of managing the brightness of the scene could be through use of the iris. However, in cases where the camera is inaccessible or when it is not practical to change the iris of the camera manually, lenses with electronically controlled irises are useful.

P-Iris lenses, where the "P" stands for "Precision," are new to the machine vision market and are also commonly referred to as "stepper-motor iris" lenses. These lenses are powered by the camera and use a precise stepper motor to set the aperture of the camera. It is the successor to DC-Iris and has eliminated some of the drawbacks seen with DC-Iris lenses such as the inability to set the aperture to a specific value consistently, having the iris setting change over time, and poor accuracy with mid-range aperture values. The key to these improvements is the P-Iris' stepper-motor which is excellent at selecting a specific point in the motor's range of motion.

Conclusion

When selecting a lens for a vision system, start with the geometric restrictions to determine the focal length of the lens based on working distance and required field of view. Next, determine the resolution required from the camera to resolve the smallest amount of visual data for the system. Once the camera has been selected, match the lens' design to the size of the camera's image sensor. Finally, ensure that the resolution rating of the lens is within the resolution of the camera to ensure that visual data is not lost through the lens.

It is important to note that some lens manufacturers promote lens resolution capabilities in terms of megapixels and others in terms of pixel size. These are both valid ways of characterizing a lens as long as the image circle of the lens is matched to the sensor size of the camera. Pairing a lens with a camera based on pixel size allows a lens to be selected which has an image circle that is not matched to the camera's sensor. While there are drawbacks associated to this, as long as they are understood and taken into account in the system's design, it is possible to use a mismatched lens and camera while maintaining the system's required resolution. This may be necessary if certain design requirements are quite stringent and the selection of a properly paired lens and camera system are physically unattainable or too costly.

Finally, be sure to test the final lens-camera pairing(s) in a physical environment to ensure that they perform as expected and that it can be confirmed that the smallest visual details are adequately resolved by the vision system.

Lens Selection Shopping List

Determining as many of the below factors as possible before shopping for a lens will help narrow the search for a lens that works with your vision system.

System Geometry

Working Distance [WD] (Distance camera can be from scene)	Minimum:	Maximum:
Field of View [FoV] (Area of the scene camera can see)	Width [FoVW]:	Height [FoVH]:

Camera Specifications

Camera:	**Sensor Format:**	**Pixel Size:**	**Camera Resolution:**
[dW] Horizontal Resolution × Pixel Size ÷ 1000 = (Area of the scene camera can see)		**[dH] Vertical Resolution × Pixel Size ÷ 1000 =** (Sensor Height in mm)	

System Geometry

Ensure all dimensions are in millimeters for correct calculation.

$$\frac{d_W \times WD}{FoV_W} = f \qquad \frac{d_H \times WD}{FoV_H} = f$$

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.

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