Choosing the Best Camera Lens

Application Note 1221

Choosing a Lens

At first glance this seems a simple task, but you will be faced with many options and questions. Choose a good supplier. You will be better off talking to suppliers that design their own lenses, even if you only need an off-the-shelf version. They will fully understand all the issues and help you the most. The supplier will start asking you questions that this paper will try to answer, including:

1. Image circle
2. Focal Length/Field Angle
3. F-number
4. Resolution
5. Distortion
6. Cost

Table 1.

Lens Size (inch)	Image Size Diagonal (mm)	Image Size Horizontal (mm)	Image Size Vertical (mm)
1	16	12.8	9.6
2/3	11	8.8	6.6
1/2	8	6.4	4.8
1/3	6	4.8	3.6
1/4	4	3.2	2.4

Table 2. Image Diagonal of Various Sensor Types

Part Number	Sensor Type	Horizontal Pixel Count	Vertical Pixel Count	Pixel Pitch (µm)	Image Diagonal (mm)
HDCS-1000	CIF	352	288	7.8	3.55
HDCS-1020	CIF	352	288	7.4	3.37
HDCS-2000	VGA	640	480	9.0	7.20
HDCS-2020	VGA	640	480	7.4	5.92

Image Circle

Lenses are first organized by sensor size. Back in the early days of vidicon tubes you ordered lenses by what size image tube you had. A one-inch vidicon tube (outside diameter) required a one-inch lens. The image used on a one-inch tube was only 16 mm (not 25.4 mm). All video lenses are based on this standard. Refer to Table 1.

The chart shown in Table 2 is based on the TV standard where the horizontal to vertical ratio is 4:3. Your CMOS imager may not have this ratio. Just make sure the diagonal of the imager matches the diagonal of the lens. You might be asked, “Is this a 1/4 inch sensor?” This equates to a 4 mm image diagonal. Table 2 shows the image diagonal of various sensor types.

Both the pixel counts and pixel size determine the image diagonal. Choose a lens with an equal or larger image size (also called the image circle).

Focal Length/Field Angle

The next choice will be the field angle. This is a measure of how wide or narrow the field of view is. On a 35 mm film camera, a 28 mm focal length lens is called a wide-angle lens. A 50 mm is “normal” and a 135 mm would be telephoto. Once again these numbers are related to the image diagonal. On 35 mm film the image size is 24 mm x 36 mm, resulting in an image diagonal of 43.27 mm. A true “normal” lens would have a focal length of around 43 mm (50 mm is close). Lenses with more than 43 mm would magnify the image (telephoto) and lenses with less than 43 mm would be wide-angle. The actual field of view is measured in degrees. This can be specified as a horizontal field of view or an image circle field of view. Be careful and be specific. Different people use different definitions. If you ask a lens

Table 3.

Lens Focal Length (mm)	Horizontal Image Size (mm)	Vertical Image Size (mm)	Diagonal Image Size (mm)	Field Half Angle	Horizontal Angle	Vertical Angle
28	36	24	43.3	37.7	65.5	46.4
50	36	24	43.3	23.4	39.6	27.0
135	36	24	43.3	9.1	15.2	10.2

Lens Focal Length (mm)	Horizontal Image Size (mm)	Vertical Image Size (mm)	Diagonal Image Size (mm)	Field Half Angle	Horizontal Angle	Vertical Angle
4	4.74	3.55	5.92	36.5	61.3	47.9
7	4.74	3.55	5.92	22.9	37.4	28.5
19	4.74	3.55	5.92	8.85	14.2	10.7

designer, field angle is defined as the angle from the center of the image to the corner of the image (the half angle of the image circle cone). Many lenses will use the full horizontal angle. That would be the angle between the left most part of the image to the right most part of the image as measured from the position of the camera.

Angles can be calculated from the focal length of the lens and the image size.

Angle = arctangent (image size/2 / focal length)

You will see that the 4 mm lens, in this case, is roughly equivalent to a 28 mm lens on a 35 mm camera.

f-number

The f-number of the lens will determine the amount of light gathered by the lens. Typical values will be from f/1.8 to f/4.0. If the camera is to be used indoors then a faster lens (lower f-number) would be better. Outdoors an f/4.0 will be fine and give you more depth of focus. The amount of light gathered can be calculated as a function of the square of the f-number. So the difference between an f/2.0 lens and an f/1.8 lens is 2.02/1.82 = 1.23. So the f/1.8 lens lets through 23% more light.

Resolution

Resolution is one of the more difficult parameters. Resolution test charts are often used to measure cameras. Consider the following test target:

Figure 1.

This target is a series of white and black stripes. One pair of lines is denoted 1/n. This is one line pair. The number of line pairs that fits in the distance of one millimeter is the target resolution. A lens looking at this target will blur the image to some degree. Each white/black or black/white edge will be spread (blurred) resulting in a ramp instead of a stair step.

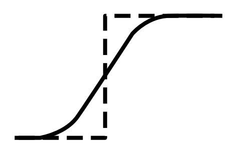

Figure 2.

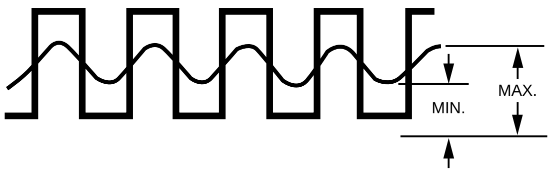

Figure 3.

If we measure the intensity of light across the target we get the graph shown above.

The resulting signal looks more like a sine wave. The signal will go entirely to black or entirely to white. This is a measure of the contrast of the signal and lens. As the target blurs it appears to get gray. An image with poor contrast will look washed out. The contrast can be measured as MAX-MIN. A more common measurement is the modulation transfer function (MTF) calculated as [MAX – MIN] \ [MAX + MIN]. MTF values are only valid for a particular test frequency (lp/mm). In a CMOS imager application, the test frequency is related to the pixel pitch. If the lens is to resolve single pixels then the MTF should be measured at the correct pixel pairs per millimeter. For 7.4 µm pixels (i.e. HDCS-2020 CMOS imager) this would be 67.5 lp/mm. This might be a reasonable number to use if the pixel has a 100% fill factor. The actual active area of the pixel is smaller than 7.4 µm.

Here is what a pixel looks like:

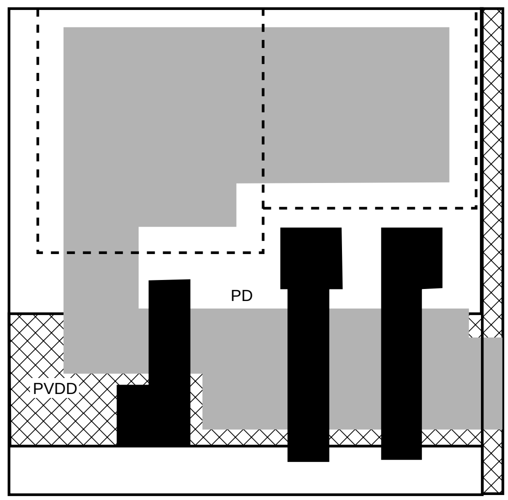

Figure 4.

It contains the photodiode and three transistors. The part of the pixel that is sensitive to light is shown here:

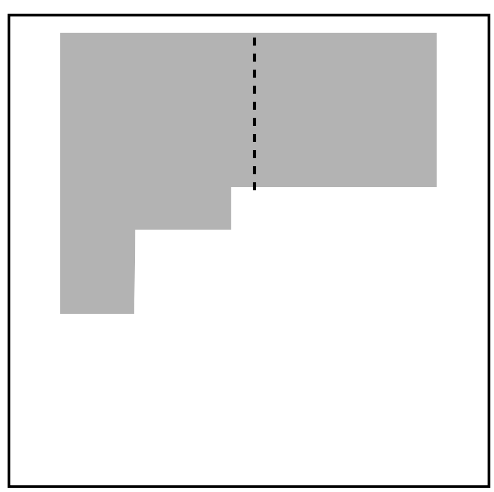

Figure 5.

So let's consider an array of these pixels and the image blur spot of our lens. The image in Figure 6 shows the array with two blur spot sizes. The smaller circle is a lens that is designed to have a good MTF at 55 lp/mm (9.0 µm diameter blur). This lens will resolve single pixels. The larger circle shows a lens that has a good MTF at 33 lp/mm. (15 µm diameter blur). This lens will not resolve single pixels and will blur the image. Since the array is a Bayer color pattern it will also reduce the color contrast of the scene.

So, what is a good MTF number? A good lens will have an MTF of 30 to 50%. A lens designer might design the lens for 50% and after production and tolerances the final lens will measure about 30%. Ask if the MTF is a design number or measured in production. The MTF of a lens will not be the same in the center of the image and the corners. Generally, the center will have much better MTF (maybe double) and the corners of the image will be a bit blurrier. An example of a lens specification might be 50% MTF @ 55 lp/mm in the center of the field and 30% MTF @ 55 lp/mm in the corners. Many designers consider the "corners" to be 71% of the way from the center to the corner, not the extreme corner.

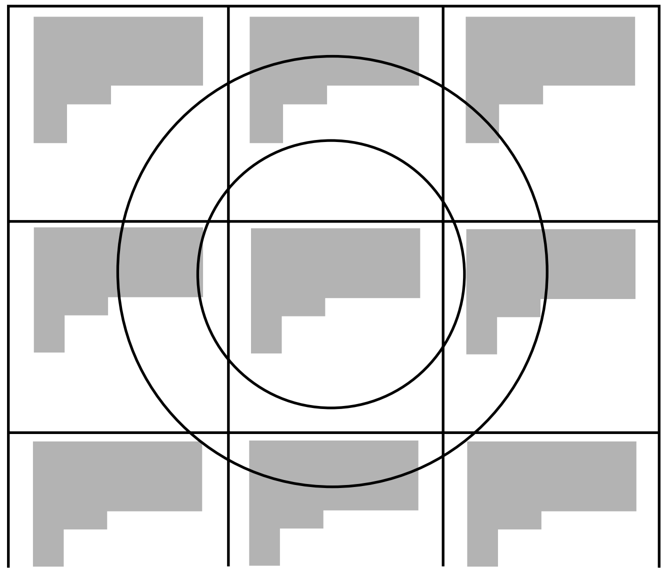

Figure 6.

Distortion

Distortion causes the image to be bent. Straight lines will appear curved. Distortion is measured in percent. For comparison, a typical computer monitor will have about 2% distortion. The diagrams in Figure 7 show various levels of distortion.

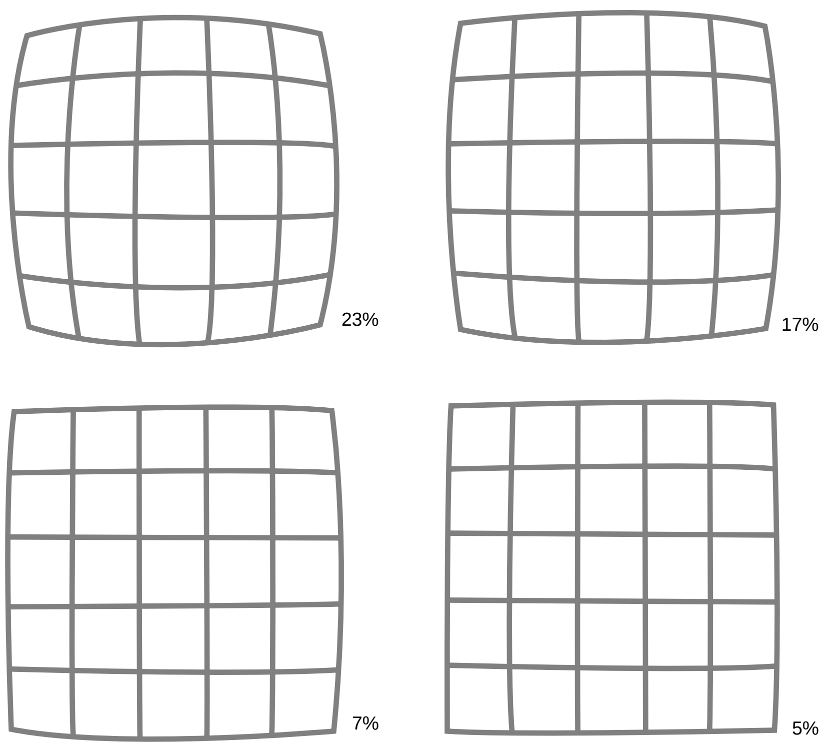

Figure 7.

Cost

You usually get what you pay for. One rule of thumb is each element in a lens costs about one dollar. So expect to pay $4 for a 4-element lens. While you might think plastic will be cheaper, do not rule out glass designs. It is difficult to mold a high performance plastic lens and there will be large variations part-to-part. Glass is very repeatable and is stable over temperature and humidity variations.

Conclusion

Many requirements such as f-number, field angle, resolution, and cost are inter-related and you will have to make compromises. Also, remember that lenses are very easy to design on paper (or in the CAD program). The proof will be actual measurement made with actual lenses.

Definitions:

- MTF: modulation transfer function
- Square wave MTF: most often used to do measurements. The use of a USAF test chart will result in a square wave MTF. Usually the square wave MTF number is lower than the sine wave and therefore more conservative.
- Sine wave MTF: this is the true definition of MTF. Special printed sine wave test charts can be purchased
- Contrast
- Resolution this is very confusing and misused term.
- Lp/mm: line pairs per millimeter. A test target consists of equal width white and black stripes. One white and one black stripe is a pair. The number of pairs per millimeter used to describe this.
- Determining MTF by viewing.
- USAF test chart.
- Astigmatism: blurriness in different directions. Specifically the two directions are along radial lines from the center or along concentric circles emanating from the center (radial and tangential, also called sagital and tangential). The USAF test chart has horizontal and vertical targets. You will find that one of these will be more in focus than the other. Some test charts have the bar targets at an angle in the corners to accurately measure this.
- Sharpness in the corners: lenses in general are not as sharp in the corner and the MTF specification may account for this. You might have say 50% MTF at 50 lp/mm in the center and 30% MTF at 50 lp/mm in the corners. You might also see a spec of 30% MTF measured at 50 lp/mm in the center and 30 lp/mm in the corners.
- Contrast
- Flare: not all the light will focus to perfect spots. Light that gets through the lens but not where you would like it will add to an overall wash of light. This wash of light will reduce the contrast of the image by adding an offset. A good lens is designed to reduce flare. Even a good lens can show this effect if the subject is strongly backlit.
- Color range: The lens designer will use three (sometimes more) colors of light in the calculations of his design. The Fraunhofer lines are commonly used (656.3 nm, 589.2 nm, 486.1 nm). These single values of red, green and blue set the working wavelength range of the lens.

- Lateral color: this is a change in magnification that is color specific. For instance, the blue image and red image will be different sizes. This is usually worse at the edge of the image and will appear as a color break-up. A white line at the edge of the image might look like a small rainbow. If the lens is poor at blue light the line may look yellow with a blue fringe.
- Thru focus MTF: this is a graph of MTF vs. image location. This can be used to determine focus error tolerancing, coplanarity requirements, and depth of field (depth of focus).
- Polychromatic: pertaining to a range of color (usually white light)
- Monochromatic: pertaining to a single color of light
- Viewing angle
- f / # or f-number: a measure of how much light the lens can capture. An f / 1.8 lens will let through more light than an f / 4.0 lens. Each factor of 1.414 will let through twice as much light.
- Distortion: straight lines will look bent.
- IR filter
- Cost
- Size: the lens has to fit where you want to use it
- Thread size: there is an amazing range of sizes used. Choose carefully as some sizes are so rare that machine shops cannot cut the threads.
- Lens mount: holds the lens and blocks stray light. It might mount on the PC board or directly to the imager package
- Planarity
- Coatings -
  AR coating - antireflection coating. Every glass/air surface reflects about 4% of the light. A good AR coat can reduce this to less than 0.5%.
- Transmission: percent of photons that make it to the other side. A four element uncoated lens will only pass 68% of the photons due to reflections.
- Vignetting: higher angle rays of light might not get through the lens. The clipping of rays is called vignetting. The lens designer might do this intentionally to reduce the f-number at the corners of the image. If is difficult to design a lens for sharp corners and this "trick" is often used. This can cause dark corners in your image.
- Cos^4, Uniform intensity, relative illumination: Most lenses will pass more light to the center of the image resulting in darker corners.
- Image circle

Reference:

1. Modern Optical Engineering, Warren Smith, ISBN 0 07 059174 1
2. Applied Photographic Optics, Sidney F. Ray, ISBN 0 240 51499 8

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