Optics 101

Selecting the right optical components to use in your imaging application is a very important decision. Generally, it seems that the selection of the optics becomes a second thought in the design of an imaging system, when it should be among your first. It is along the optical path, through the lens, that an image is transferred to the image sensor in the camera. The optical system controls the amount of light that reaches the image sensor, the magnification of the image, and the field of view. Depending on the application, the quality of the lens can become a critical consideration, especially when you start to consider issues of distortion and aberrations.

Lens Selection

The camera is usually the first item selected when building an application. Sensor type and resolution are determined based on the required object resolution. Once a camera has been selected, compatible optics are generally predetermined by the mount that is supplied with the camera. The most popular mounts are the C-mount and the Nikon F, but cameras with mounts compatible with other lens manufacturers are also available. The nice thing about having a camera configured for a specific lens type is that the back focal distance is preset. The C-mount's back focal distance is 17.53mm, and the Nikon F's is 46.5mm. A variation on the C-mount lens is the CS-mount, which is the same thread size as the C-mount but with a back focal distance of 12.5mm. Note, a CS-mount lens will not be able to focus properly on a camera configured for a C-mount lens. You can install a CS-mount lens onto a camera configured for a C-mount lens if you include a 5mm spacer between the mount and lens. With a preset back focal distance there is no need for further complex lens configuration details. You can be assured that when you attach your lens it will focus from infinity down to the minimum distance capable with the lens focus system.

When dealing with the C-mount lenses, it is important to consider the physical size of the camera sensor. The C-mount lens comes in a variety of image circle specifications. An application will typically require that the image formed by the lens on the sensor cover the entire sensor. Therefore, the image circle (the diameter of the image behind the lens that is applied to the sensor) must be large enough to cover the entire sensor array.

Figure 1. Nikon F Lens

Figure 2. C-mount lenses

Maximum Sensor Dimensions for C mount lenses			
Image Circle (in)	Vertical (mm)	Horizontal (mm)	Diagonal (mm)
1/4	2.4	3.2	4
1/3	3.6	4.8	6
1/2	4.8	6.4	8
2/3	6.6	8.8	11
1	9.6	12.8	16

Lenses that are used with popular 35mm cameras will have an image circle on the order of approximately 42.4mm in diameter.

Determining Lens Focal Length

Selecting the proper optics starts with the application. What is it that you are imaging and what is the smallest feature size that is of interest? The answer to these two questions will determine your field of view and your magnification requirements. For example, consider an imaging application for document scanning, where the objects will be standard 8.5” x 11” sheets of paper and you will need to obtain a resolution of 300 dots per inch (dpi). Because you require high-speed imaging, the camera selected will be a line scan camera.

You have defined the field of view (FOV) as 8.5”. With the required resolution of 300dpi, you can determine the necessary image sensor resolution as 8.5” x 300dpi = 2550. In other words, one scanned line will be composed of 2550 individual samples. This is the first step in determining the available camera resolution. You now know that you must select between camera resolutions of 2048 or 4096 pixels. Selecting a 2048 resolution camera will give you less than 300dpi (actually 241dpi), and a camera resolution of 4096 will give you more than 300dpi (actually 482dpi). A camera with a sensor resolution closer to the desired one may be available, but for the sake of simplicity you choose a 2048 pixel resolution camera.

You can now determine the necessary magnification using the camera specifications and the object feature size. Magnification is always defined as the ratio of the camera's image sensor pixel size divided by the minimum feature size of the object. Since you will be imaging the 8.5" FOV onto a 2048 sensor, the minimum object feature size becomes 8.5" / 2048 = 0.0042". (Translated into metric units, the object feature size becomes 0.1054mm.) From the camera specifications, you know that the camera's imaging sensor has a pixel size of 0.014mm. You can determine the magnification by dividing the pixel size (0.014) by the feature size (0.1054), for a resulting magnification of 0.1328.

Magnification = Pixel Size / Minimum Object Feature Size

You can now find out what the focal length of the lens should be. You have determined the magnification of the system, but you need to know either the working distance from the front of the lens to the object, or the focal length of the chosen lens. Knowing one of these parameters will allow you to determine the other. The application may put some constraint on the working distance between the object and the front of the lens, or you may have a specific lens that must be used for the application.

For this example, you define the working distance from the object to the front of the lens to be roughly 12" (305mm). You now have enough information to determine the focal length (FL) of the lens. Find the focal length by dividing the working distance (305mm) by 1 plus the value of 1 divided by the magnification (0.1328), for a resulting focal length of 35.8mm.

Focal Length = Working Distance / (1 + (1 / Magnification))

Therefore, a 35mm lens will suit your application. All that is left now is to select a lens based on quality, price, and availability, mount it on the camera and put it into use.

Focus

If you use a lens that incorporates an integral focus mechanism and your object lies within a distance between infinity and the minimum focus distance of the lens, you should not have to worry about being able to bring your image into focus.

If you find that the object is positioned closer to the lens than the minimum focus distance permitted, it is possible to include a spacer between the lens and the camera that may allow you to focus the image. The success of a spacer is based on the principal that as an object moves closer to the camera, the lens must move further out from the CCD in order to focus properly. This is normally what happens when you adjust the integral focus mechanism of a lens. However, there is a limitation on the travel of the focus mechanism. Including a spacer between the lens and the camera allows you place an object closer to the lens than recommended by the minimum focusing distance, but you will no longer be able to focus at infinity.

It is possible to determine what back focal distance you will require for a specific working distance. A lens specification sheet will provide you with the back focal distance of a lens. This specification is the fixed distance between the mounting surface of the lens and the CCD, and is specified at infinity. As the distance between the object and the front of the lens decreases, the back focal distance increases.

Change in Back Focal Distance = (Focal Length^2) / (Working Distance – Focal Length)

For example, if we are currently using an F-mount 35mm lens with a back focal distance of 17.54mm, and our working distance from the front of the lens to the object is 305mm, then the change in back focal distance when the object is in focus is:

$$35\text{mm}^2 / (305\text{mm} - 35\text{mm}) = 4.54\text{mm}$$

Since this is the change in back focal length, then the total back focal length when the image is in focus is 17.54 + 4.54 = 22.08mm. Usually this change can be accomplished with a focus mechanism.

If you include a lens spacer to reduce the minimum focus distance, you will want to remember that there is a limit on how close you can bring an object to the lens and still maintain a quality image. When an application requires a very near focus distance or high magnification, then standard off-the-shelf lenses may not suit your requirements.

Special Lens Considerations

If your application requires an unusually small working distance, high magnification, or minimum distortion, it may be necessary to use a special type of lens. The best approach is to consult with a reputable lens manufacturer who can lead you a specific line of lenses that will meet your particular needs. As well as lens selection, a lens manufacturer can provide you with the assistance that you may require to incorporate the special lens onto your camera and into your application.

For example, suppose your requirement is to view an object with a 1.5” (38.1mm) field of view onto a CCD which is 2048 pixels wide and has a 0.014mm pixel size. The imager’s total horizontal dimension is 2048 x .014 = 28.7mm.

First, determine the magnification, which can be calculated by dividing the imager size (28.7) by the field of view (38.1), for a value of 0.75. This is approaching a magnification of 1:1 and therefore, you would require a lens that is specialized for high magnification.

After consulting with various lens manufacturers, you find a suitable lens that is available in an 80mm focal length. You can now determine the working distance of your application using the following formula:

$$\text{Working Distance} = 80\text{mm} \times (1 + (1 / 0.75)) = 187\text{mm } (7.4")$$

The same formula can be used if you are restricted to a certain working distance, and want to determine the lenses required focal length.

You now have to determine the back focal distance of the lens. This lens has a flange focal length of 80.34mm, at infinity, as specified in the lens’ specification sheet. You can determine how much the flange focal length will change for an object distance of 187mm as follows:

$$\text{Change in focal distance} = (80\text{mm})^2 / (187 - 80.34) = 60\text{mm}$$

You now know that the total flange focal length required is 80.34 + 60 = 140.34mm. This is the total distance required from the lens’ mounting flange to the CCD. The distance of 60mm must be built up and will include the distance from the CCD to the existing lens mount plus various dimensions of spacers. You should also include a focus mechanism in the lens spacer arrangement for fine tuning the focus and to account for the dimension of the focus mechanism. The focus mechanism will have a minimum and maximum dimension. When determining the various spacer dimensions, use a dimension for the focus mechanism that is midway between the maximum and minimum distance.