Ten lens specifications you must know for machine-vision optics

Gregg Fales - October 27, 2003

Machine-vision integrators and designers, faced with challenging hardware, software, and electronic issues, often overlook optical performance specifications. Without understanding how to assess the optics, however, the task of choosing among machine-vision lenses quickly becomes overwhelming. By understanding these ten specifications, integrators and users select the appropriate lens to optimize their system’s performance.

Figure 1. Basical optical parameters of a machine vision system include the field of view, working distance, resolution, and depth of field. (Magnification is not a basic parameter.)

The four most basic parameters in specifying the optics for a vision system are field of view, resolution, working distance, and depth of field (Figure 1). Other specifications to consider in advanced integration are the f/#, maximum chip format, distortion, zoom/focus features, design conjugate, and telecentricity.

The big four

Simply put, the field of view should be the size of the object you need to inspect. Many engineers tasked with specifying a machine-vision system think in terms of magnification. Magnification, however, is a relative specification and depends on the size of the image sensor and the size of the display device—it has no real meaning in terms of field of view or resolution. For example, a system with a 50X magnification can have a field of view of 5.3 mm (if the system uses a 1/2-in. CCD and 13-in. monitor) or a field of view of 15.2 mm (1-in. CCD, 19-in. monitor). You must specify the field of view to ensure that the vision system can inspect the entire region of interest.
Specifying the field of view rather than the magnification also ensures that the system will have the appropriate resolution. The resolution of the system is the minimum distinguishable feature size of the object under inspection. In most instances, the smaller the field of view, the better the resolution. The resolution of the system is determined by the modulation transfer function (MTF) of the optics, camera, cabling, and display hardware. MTF qualifies the overall imaging performance of a component in terms of resolution and contrast.

Too often, the MTF of the optics is ignored, and the resolution of the system is calculated based on primary magnification and camera pixel size. This approximation assumes perfect optics and generally leads to under-specifying the lens and degrading the performance of the system. Knowing how accurately the lens transfers data from the object onto the camera chip allows the integrator to maximize the system’s field of view while maintaining appropriate resolution for the task at hand.

(Bonus tip: MTF is not just for lenses. Even the non-optical components in the system have associated MTF curves that contribute to the system MTF: you can avoid over- or under-specifying the performance of these components by making sure the MTFs of all the components complement each other.).

![Modulation Transfer Function](image)

**Figure 2.** Increasing the size of the aperture will often increase the resolution of the lens.

Sometimes mechanical constraints dictate difficult optical constraints. The working distance is the distance from the front of the lens to the object under inspection. The longer the required working distance, the more difficult and more costly it becomes to maintain a small field of view. Often, a small field of view will be specified out of necessity with a fairly long working distance specified out of convenience. This configuration, however, greatly increases cost and typically reduces the resolution and light collection ability of the optics, unnecessarily degrading the system’s overall
imaging performance. Where mechanical constraints exist (for example, imaging a reaction inside a vacuum chamber), this configuration may be necessary. If a long working distance isn’t necessary, though, don’t complicate matters needlessly.

If the objects to be imaged are three dimensional, then you must also consider the depth of field. The depth of field of a lens is its ability to maintain a desired resolution as the object is positioned closer to and further from best focus. A large depth of field can simplify mounting constraints, because precision movement is not necessary to position the object at the nominal working distance of the lens. However, keep in mind that although the lens will maintain the minimum resolution over the specified depth of field, the lens won’t necessarily maintain the same field of view over that depth. This change in magnification can have disastrous results on machine vision measurement applications. (Telecentric lenses – discussed below -- minimize this problem.)

**Important subtleties**

Specifying field of view, resolution, working distance, and depth of field is enough to choose an appropriate lens for your machine-vision system. By considering other factors as well, including illumination integration, CCD format, operator error, and software development, you can reduce setup costs and system downtime while optimizing reliability and repeatability.

Depth of field, to a great extent, is controlled by the f/# of the lens. The f/# is the ratio of the focal length of the lens to the diameter of the aperture stop. In an ideal lens design, the f/# is the limiting factor in system resolution. Common machine-vision optics integrate an adjustable iris into the design, allowing the user to adjust for varying light levels and to control the depth of field. Increasing the size of the aperture decreases the depth of field, but will often increase the resolution of the lens (Figure 2). Decreasing the size of the aperture (commonly referred to as “stopping down” the lens) increases the depth of field, but decreases the effective diffraction limit of the lens. This degrades overall system performance.

Note that f/#, resolution, and depth of field are interrelated. Given a required resolution and depth of field, the manufacturer of your machine-vision optics will be able to determine the ideal aperture setting of your lens. In other words, if you plan to integrate an off-the-shelf lens into your machine-vision system, the initial lens selection should be based on required working distance and field of view. The optics manufacturer should then work with you to determine whether the lens you’ve selected will be able to achieve the desired resolution, at the necessary contrast level, with the appropriate depth of field.

The maximum CCD format is an often-overlooked and misunderstood specification of machine vision lenses--partly because manufacturers are not all measuring the same thing. To some, the maximum CCD format is the length of the diagonal of a common CCD chip that most closely matches the diameter of the image the lens will produce without vignetting. Other manufacturers, however, specify the maximum CCD format as the largest diagonal the lens will cover while maintaining specified resolution and distortion characteristics. As Figure 2 shows, the resolution of the lens degrades as the image moves off axis. If the first definition (coverage without vignetting) of maximum CCD format is used, your system will maintain the specified resolution only in the center of the chip. If the object under inspection has critical details towards the outer edges of the image, those details may not be resolved if your system incorporates the maximum specified sensor format. It’s important to know how the optics manufacturer is specifying the maximum format to avoid losing critical information about your object.

Distortion is an optical error that causes differences in magnification of the object at different points on the image. The information about the object is not lost, merely misplaced, so distortion can be
calculated out of the final image. Some integrators elect to develop software to remove the distortion, rather than specify optics that have inherently low distortion. This method, however, leads to increased costs in overhead, as the software takes time to develop, specific test targets must be purchased to determine levels of distortion, and the targets and optics need to be periodically recalibrated to ensure system accuracy. Well-designed, long-focal-length optics inherently minimize distortion and typically prove to be a more economical and more reliable long-term solution, though they do so at a cost of increased working distances. If system constraints require a short working distance and a large field of view, often an off-the-shelf solution is not available and, other than a custom lens, a software solution may be the only reasonable fix.

Increased distortion can also arise when machine vision lenses are designed to be too modular. Features including focus knurls, adjustable irises, and zoom functions greatly increase design and manufacturing costs while limiting overall performance. The enhanced features allow the manufacturer to market the lenses for a variety of applications and end-user markets, but the increased flexibility generally decreases resolution and throughput, increases distortion, and creates user error. When the software of the machine-vision system is calibrated to a specific field of view and aperture setting, any adjustment of the iris, zoom, or focus of the lens requires recalibration (leading to system downtime) or else compromises reliability. For an OEM application, custom optics designed specifically for your field of view, working distance, resolution, and depth of field would eliminate these problems, but long lead-times and high design and manufacturing costs only make the custom solution practical for large-volume requirements. Integrators for small-volume requirements should be careful to select lenses that minimize the risks associated with these flexible features by selecting lenses without them, or by selecting lenses with lockable focus, iris, and zoom functions. However, these functions are very useful for prototype and proof-of-concept work, as they can assist the integrator in determining precise field-of-view and depth-of-field settings.

Lens housings that include threads for screwing on filters can enhance the system’s performance. Filter threads simplify the addition of color filters, neutral density filters, or polarizers to a machine-vision system (which can enhance contrast levels, reduce glare, and improve system accuracy). The filter threads can also be used to easily integrate illumination, thus simplifying mounting and reducing custom machining costs.

**Know the design**

While most machine-vision optics manufacturers are unwilling to release the optical design of their lenses, it’s important to get as much information as possible about the design criteria. One common mistake integrators make is to ignore the design conjugate of the optics (i.e., the optimized distance from the object plane to the lens) and to use a lens at a short working distance when it is designed to focus at infinity. You can force such a lens to focus at very short distances by adding spacers, but the overall performance is likely to suffer: An otherwise well-designed lens may exhibit increased distortion, chromatic and spherical aberrations, reduced depth of field, non-uniform illumination, and decreased light gathering ability. These problems become more prevalent as the lens is forced further and further from the situation for which it was designed.

One popular method for reducing magnification changes over different depths of field is to use lenses designed to be telecentric. Maintaining constant magnification is very important in machine-vision-based measurement systems. Using telecentric lenses, movement of the object toward or away from the lens (e.g., bottles bouncing down a conveyor belt) will not result in the image getting bigger or smaller, and an object which has depth or extent along the optical axis will not appear as if it is tilted. Calibrated software can then directly measure the size of the object.

**Apply smarts and reduce costs**
The more information a machine-vision optics manufacturer can provide you about the lens for your system, the more likely your project is to succeed. For simple inspection and go/no-go systems, choosing a lens with the proper field of view at the proper working distance may be all you need. For more demanding applications, however, the choice of optics becomes critical to the system’s success. Working with an optics manufacturer capable of providing tested MTF data, meaningful depth of field information, and knowledgeable support about how the lens performs in the application removes the guess-work from the system integration and allows the integrator to concentrate on the more time consuming hardware and software issues. 

**Gregory Fales** is applications engineering manager at Edmund Industrial Optics in Barrington, NJ. He has three years of experience in the machine-vision industry. He has a B.S. in optics from the University of Rochester.