Machine Vision Lens Fundamentals

All the information collected by a machine vision system comes through the lens. The correct choice of lens can reduce image-processing requirements and improve system performance and robustness. Software cannot correct the effects of a poorly chosen lens.

This primer provides the technical and practical information needed to choose a lens for a machine vision system. First we review design principles, providing simple formulas that form the basis of further calculations. From models, we proceed to a discussion of real-world lenses and practical parameters. A discussion of special lenses completes this section.

First-Order Design Theory

To establish an understanding of theoretical principles, we will first review a few basic lens definitions and parameters. We then examine the thin-lens model. The thin-lens model describes a lens with no limitations — one that can be used at any magnification and work at any conjugate. However, since real lenses do have limitations, the thin-lens model does not provide the complete picture. Following this theoretical discussion, we will examine real lenses and their parameters, as well as special lenses.

CAMERA FORMAT

The camera format defines the dimensions of the image sensor. Lenses, by design, provide images over a limited area. Be sure the lens covers an area as large or larger than the camera format.

FIELD OF VIEW

The field of view (FOV) is the object area that is imaged by the lens onto the image sensor. It must cover all features to be measured, with additional tolerance for alignment errors. It is also good practice to allow some margin (e.g., 10 percent) for uncertainties in lens magnification. Features within the FOV must appear large enough to be measured. This minimum feature size depends on the application. As an estimate, each feature must have three pixels across its width, and three pixels between features. If there are more than 100 features across a standard camera field, consider using multiple cameras.

MAGNIFICATION

The required magnification (m) is

$$\text{mag} = \frac{W_{\text{camera}}}{W_{\text{FOV}}} \qquad (6.1)$$

where W_{camera} is the width of the camera sensor and W_{FOV} is the width of the FOV. Note that the required magnification depends on the camera sensor size.

WORKING DISTANCE

The working distance is the distance from the front of the lens to the object. In machine vision applications, this space is often needed for equipment or access. In general, a lens that provides a long working distance will be larger and more expensive than one that provides a shorter working distance. The back working distance is the distance from the rear-most lens surface to the sensor.

THIN-LENS MODEL

To understand machine vision lenses, we start with the thin-lens model. It is not an exact description of any real lens but illustrates lens principles. It also provides terms with which to discuss lens performance. A ray, called the chief ray, follows a straight line from a point on the object, through the center of the lens, to the corresponding point on the image (figure 6.1). The lens causes all other rays that come from this same object point and that reach the lens to meet at the same image point as the chief ray. Those rays which pass through the edge of the lens are called marginal rays.

The distance from the object plane to the lens (s_1) is called the object conjugate. Likewise, the distance from the lens to the sensor plane (s_2) is called the image conjugate. These conjugates are related by: .

$$\frac{1}{f} = \frac{1}{s_1} + \frac{1}{s_2} \quad . \qquad (6.2)$$

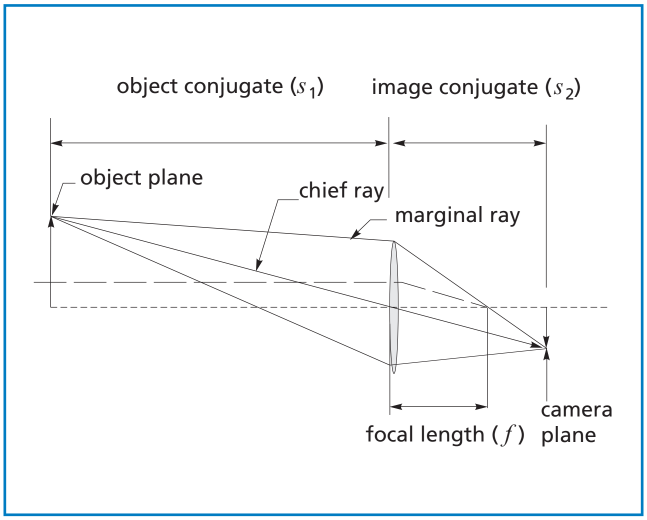


Figure 14.1 **Thin-lens model**

FOCAL LENGTH

If we let the object conjugate get very large, we see

$$\frac{1}{f} \approx \frac{1}{s_2} \Rightarrow s_2 \approx f \, . \tag{6.3}$$

In other words, the focal length is the distance between the lens and the sensor plane when the object is at infinity. For photographic lenses, the objects are usually far away, so all images are formed in nearly the same plane, one focal length behind the lens.

From geometry, we can see that .

$$m = \frac{s_2}{s_1} \, . \tag{6.4}$$

The magnification is the ratio of the image to the object conjugates. If the focal length of a lens increases for a specified magnification, both object and image conjugates increase by the same ratio.

APPLICATION NOTE

Thin Lens Example

We need a magnification of 0.5 × , with a working distance of 50 mm. We want to find the correct lens focal length and total system length (TSL). Substituting equation 6.4 into equation 6.2 and solving for *f*, we get:

$$f = \frac{m}{m+1} \times s_1$$

so

$$f = \frac{0.5}{1.5} \times 50\,\text{mm} = 16.7\,\text{mm}$$

$$s_2 = s_1 \times 50\,\text{mm} \times 0.5 = 25\,\text{mm}$$

$$\text{TSL} = s_1 + s_2 = 50\,\text{mm} + 25\,\text{mm} = 75\,\text{mm} \, .$$

Therefore, we need a lens with focal length of approximately 17 mm. The total system length is approximately 75 mm.

F-NUMBER

The f-number (f/#) describes the cone angle of the rays that form an image (figure 6.2). The f-number of a lens determines three important parameters:

- The brightness of the image
- The depth of field
- The resolution of the lens

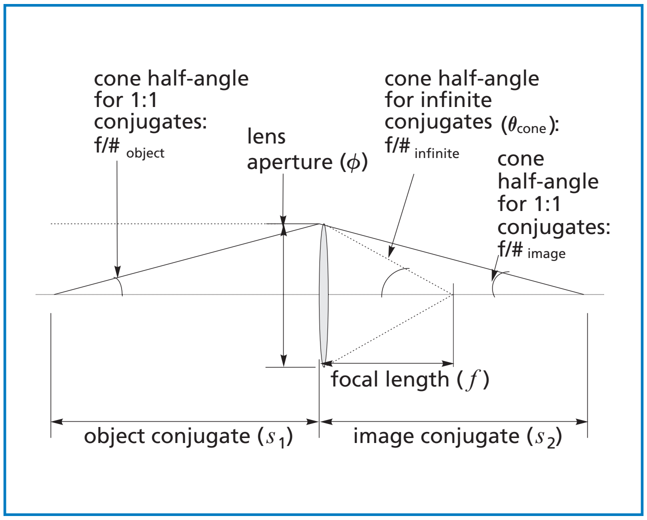


Figure 6.2 **f/number (f/#)**

For photographic lenses, where the object is far away, the f-number is the ratio of the focal length of the lens to the diameter of the aperture. The larger the aperture is, the larger the cone angle and the smaller the f-number will be. A lens with a small f-number (large aperture) is said to be "fast" because it gathers more light, and photographic exposure times are shorter. A well-corrected fast lens forms a high-resolution image but with a small depth of field. A lens with a large f-number is said to be "slow." It requires more light but has a larger depth of field. If the lens is very slow, its resolution may be limited by diffraction effects. In this case, the image is blurred even at best focus.

The f-number printed on a photographic lens is the infinite conjugate f-number, defined as

$$\text{f/\#}_{\infty} = \frac{f}{\phi} \tag{6.5}$$

where *f* is the focal length of the lens and ϕ is the diameter of the lens aperture. When the lens is forming an image of a distant object, the cone half-angle of the rays forming the image is

$$\theta_{cone} = \arctan\left(\frac{1}{2 \times \text{f/\#}_{\infty}}\right) \, . \tag{6.6}$$

This infinite conjugate f-number is applicable only when the lens is imaging an object far away. For machine vision applications, the object is usually close, and the cone angle is calculated from the working f-number.

APPLICATION NOTE

f/Number (Working)

In machine vision, the working f-number describes lens performance:

$$\text{f/\#}_{\text{image}} = \frac{s_2}{\phi}$$

$$\text{f/\#}_{\text{object}} = \frac{s_1}{\phi}$$

where s_2 and s_1 are the image and object conjugates, respectively. $\text{f/\#}_{\text{image}}$ is called the working f-number in image space, or simply the image-side f-number. Similarly, $\text{f/\#}_{\text{object}}$ is the object-side f-number.

For close objects, $\text{f/\#}_{\text{image}}$ is larger than $\text{f/\#}_{\text{infinity}}$, so the lens is "slower" than the number given on the barrel. For example, a lens shown as f/4 on its barrel (i.e., an f-number of 4) will act like an f/8 lens when used at a magnification of 1.

The object-side f-number determines the depth of field. It is given by

$$\text{f/\#}_{\text{object}} = \frac{1}{m} \times \text{f/\#}_{\text{image}} .$$

NUMERICAL APERTURE

For lenses designed to work at magnifications greater than 1 (for example, microscope objectives), the cone angle on the object side is used as the performance measure. By convention, this angle is given as a numerical aperture (NA). The NA (figure 6.3) is given by

$$\text{NA} = \sin(\theta_{\text{cone}}). \tag{6.7}$$

NA is related to f-number by these exact relationships:

$$\begin{aligned} \text{NA} &= \sin\left[\arctan\left(\frac{1}{2\times \text{f/\#}}\right)\right] \\ \text{f/\#} &= \frac{1}{2\times\tan\left[\arcsin(\text{NA})\right]} . \end{aligned} \tag{6.8}$$

For NA < 0.25 (f-number >2), these simplify to:

$$\begin{aligned} \text{NA} &\cong \frac{1}{2\times \text{f/\#}} \\ \text{f/\#} &\cong \frac{1}{2\times \text{NA}} . \end{aligned} \tag{6.9}$$

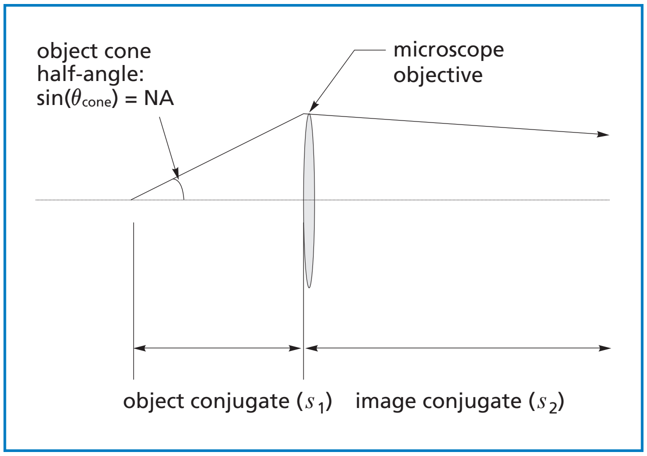


Figure 6.3 **Numerical aperture (NA)**

CNC Lens Polishing Systems at CVI Melles Griot Manufacturing Facilities

High-speed CNC grinding and polishing equipment

Close-up view of high-speed lens element polishing system

Real-World Lenses

THICK-LENS MODEL

The thin-lens model treats a lens as a plane with zero thickness. To model a real-world lens, we divide this thin-lens plane into two planes (figure 6.4). These planes contain the entrance and the exit pupils of the lens. Everything in front of the entrance pupil is said to be in object space. Everything behind the exit pupil is said to be in image space. How light gets from the entrance pupil to the exit pupil is not considered in this model.

In object space, we think of the real-world lens as a thin lens located at the entrance pupil. The entrance pupil is generally located within the physical lens, but not always. Wherever it is located, light rays in object space proceed in straight lines until they reach the entrance pupil. The effects of any elements in front of this position are taken into account when the entrance pupil position is calculated. In the same way, we think of the real-world lens as a thin lens located at the exit pupil in image space.

For many lenses, the entrance and exit pupils are located near each other and within the physical lens. The exit pupil may be in front of or behind the entrance pupil. For certain special lens types, the pupils are deliberately placed far from their "natural" positions. For example, a telephoto lens has its exit pupil far in front of its entrance pupil (figure 6.5). In this way, a long-focal-length lens fits into a short package. A telecentric lens has its entrance pupil at infinity, well behind its exit pupil (figure 6.6).

ABERRATIONS

If real lenses followed first- order theory, lens design would be easy. Unfortunately, it is difficult to make a real lens approximate this behavior. Diffraction sets a lower limit on image spot size. The differences between ideal "diffraction-limited" behavior and real-lens behavior are called aberrations.

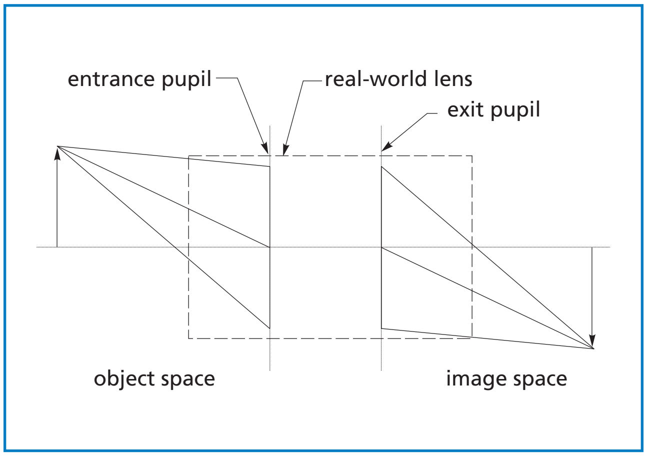


Figure 6.4 **Thick-lens model**

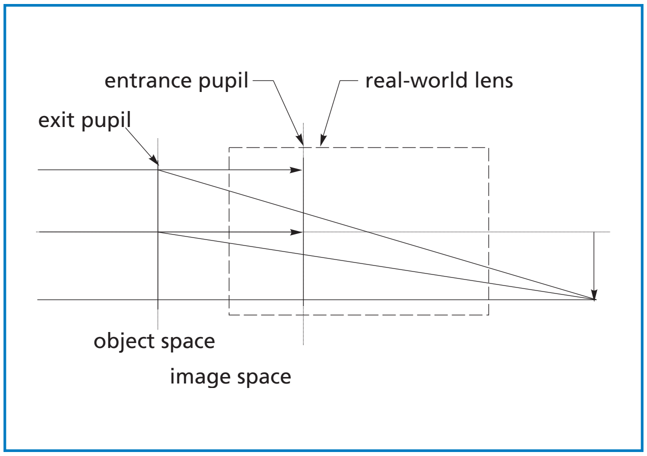


Figure 6.5 **Telephoto lens**

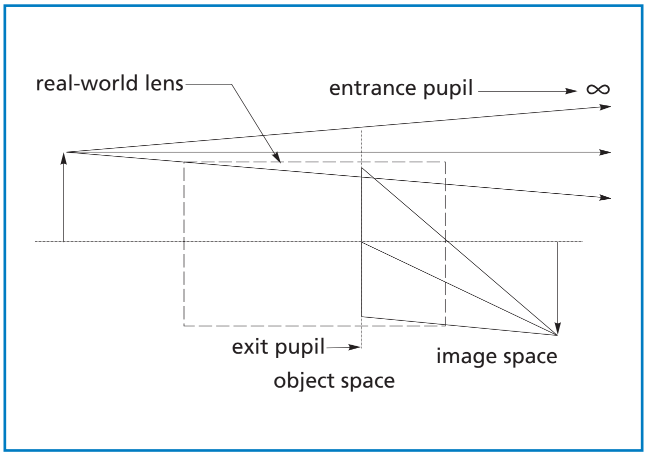


Figure 6.6 **Telecentric lens**

The job of the lens designer is to choose glasses, curvatures, and thicknesses for the lens' elements that keep its overall aberrations within acceptable limits. Such a lens is said to be well corrected. It is impossible to design a lens that is well corrected for all conjugates, FOVs, and wavelengths. The lens designer works to correct the lens over the small range of operating conditions at which the lens must function. The smaller the range is, the simpler the design can be.

A lens that is corrected for one set of conditions may show significant aberrations when used under a different set of conditions. For example, a surveillance lens with a magnification of 1/10 is corrected for distant objects. By using extension tubes, the image conjugate of the lens can be extended so that the lens forms an image at a magnification of 1. This image may, however, show significant aberrations because the lens was not corrected to work at these conjugates.

STANDARD LENSES

Commercial lenses, produced in high volume, are by far the best value in terms of performance for the price. Finding a suitable stock lens is the most cost-effective solution to a machine vision problem. The accompanying table lists various lens types and their range of operating conditions. Commercial lenses incorporate design and manufacturing techniques that are not available in custom designs. For example, a lens for a 35-mm, single-lens reflex (SLR) camera that costs one hundred dollars at the local camera store would cost ten thousand dollars to design and many thousands of dollars to manufacture in small quantities. It is always best to consider commercial lens options before initiating a custom lens design.

Common Commercial Lens Types

Lens Type	Magnification	Image Format	Object FOV (mm)	Focal Length (mm)	Working f-Number Range (Object Side)
Surveillance	<0.1	1¼″ CCD format	Large	2–50 mm	>20 (adjustable)
Standard Machine Vision	.05–5	2/3″ CCD	2–200	25–75	>4 (adjustable)
Telecentric Machine Vision	.07–5	2/3″ CCD	2–170	N/A	>6 (adjustable)
F-Mount Lenses	<1	45 mm	Large	35–100	>4 (adjustable)
Large/Medium Format Photographic	<1	80 mm	Large	50–250	>4 (adjustable)
Photographic Enlarger	2–20	500 mm	50	40–150	>4 (adjustable)
Microscope	5–100	Requires additional lens	<2	5–40	0.1–0.95 NA (fixed)

MRF Technology

Magnetorheological finishing (MRF) technology, using wavefront data from conventional and subaperture stitching interferometry, enables the production of industry's finest optical surfaces for high-precision lenses.

Real Lens Parameters

RESOLUTION

Resolution is the ability of an optical system to distinguish between two features that are close together. For example, if a lens images a row of pins on an electrical connector, it must have sufficient resolution to see each pin as separate from its neighbors. A lens imaging a lot code on a pharmaceutical bottle must have sufficient resolution to distinguish one character from another. Resolution is also required to make sharp images of an edge. A lens with high resolution will show an edge transition in fewer pixels than a lens with low resolution.

There are many different definitions of lens resolution. They differ by what type of test object is measured (points, bars, sine patterns, or other objects) and by the criteria for determining when two objects are "resolved." A practical measurement for machine vision uses three-bar targets of various spatial frequencies. A chrome-on-glass USAF-1951 target is a good test object. If the contrast between bar and space is greater than 20 percent, the bars are considered to be resolved.

Resolution does not determine the dimensional accuracy to which objects can be measured. The position of a large object can be determined to within a fraction of a resolution spot under suitable conditions. Many vision systems determine positions to one-quarter pixel. On the other hand, if the lens has distortion, or if its magnification is not known accurately, then the measured position of a feature may be in error by many resolution spot widths.

DIFFRACTION

Diffraction limits the resolution possible with any lens. In most machine vision calculations, we consider light as traveling in straight lines (rays) from object points to image points. In reality, diffraction spreads each image point to a spot whose size depends on the f-number of the lens and the wavelength of the light. This spot pattern is called an Airy disk. Its diameter is given by

$$D_{\text{Airy}} = 2.44 \times \lambda \times \text{f/\#} \qquad (6.10)$$

where D_{Airy} is the diameter of the inner bright spot, λ is the wavelength of light, and the f-number is the image side f-number. Since the wavelength of visible light is ~ 0.5 μm, this means the diameter of the diffraction-limited spot (in mm) is approximately equal to the working f-number.

For example, a typical CCD camera has pixels that are 10 μm square. To form a diffraction-limited spot of this diameter, the working f-number on the image side should be approxiamtely f/10. An f/22 lens forms an image spot larger than a pixel. Its image therefore appears less sharp than that of the f/10 image. An f/2 lens image will not appear sharper than an f/10 image, since the camera pixel size limits the resolution. In this case, the system is said to be detector limited.

CONTRAST

Contrast is the amount of difference between light and dark features in an image. Contrast (also called modulation) is defined by:

$$\text{contrast} = \frac{\text{light} - \text{dark}}{\text{light} + \text{dark}} \qquad (6.11)$$

Here, "light" is the gray level of the brightest pixel of a feature, and "dark" is the gray level of the darkest pixel. A contrast of 1 means modulation from full light to full dark; a contrast of 0 means the image is gray with no features. Finer (higher spatial frequency) features are imaged with less contrast than larger features. A high-resolution lens not only resolves finer features, but it also generally images medium-scale features at higher contrast. A high-contrast image appears "sharper" than a lower contrast image, even at the same resolution.

Factors other than lens resolution can affect contrast. Stray light from the environment, as well as glare from uncoated or poorly polished optics, reduce contrast. The angles of the lens and of the illumination have a great effect on contrast. The contrast of some objects is dependent on the color of the illumination.

DEPTH OF FIELD

The depth of field (DOF) is the range of lens-to-object distances over which the image will be in sharp focus. The definition of "sharp" focus depends on the size of the smallest features of interest. Because this size varies between applications, DOF is necessarily subjective. If very fine features are important, the DOF will be small. If only larger features are important, so that more blur is tolerable, the DOF can be larger. The system engineer must choose the allowable blur for each application.

In general, the geometrical DOF (figure 6.7) is given by

$$\text{DOF} = 2 \times \text{f/\#}_{\text{object}} \times \text{blur} \qquad (6.12)$$

where blur is the diameter of the allowable blur in object space. A larger blur or larger f-number increases the DOF.

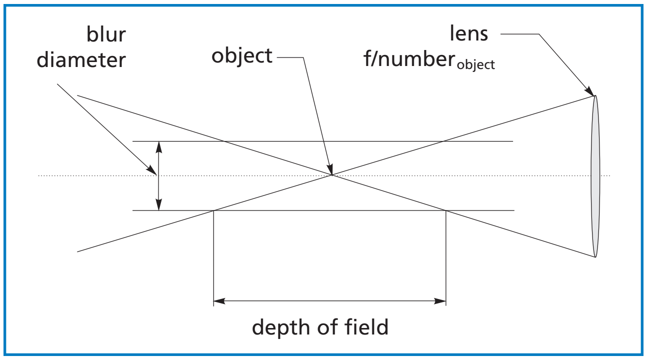


Figure 14.7 **Depth of field**

To find the DOF for detector-limited resolution, we choose the diffraction spot size created by the lens to be one pixel width in diameter, and the geometric blur caused by defocus also to be one pixel width in diameter. With these assumptions:

$$\mathrm{DOF}(\mu\mathrm{m}) = 2\times\left(\frac{W_{\mathrm{pixel}}(\mu\mathrm{m})}{m}\right)^{2} . \tag{6.13}$$

Here, we set the image side f-number of the lens equal to the pixel width in micrometers. W_{pixel} is the pixel width in micrometers; m is the lens magnification. Thus, for a camera with 10-μm pixels, operating at 0.5 × magnification, with an image side f-number of f/10, the DOF is 800 μm, or 0.8 mm.

These assumptions are very conservative. Using a higher f-number reduces the resolution of the lens slightly but greatly increases the DOF. For example, with the lens operating at f/22 and allowing a geometric blur of two pixel widths, the DOF is 3.2 mm, which is four times larger. This is a better estimate if the important image features are larger than two pixels (40 μm). The choice of f-number and allowable blur depends on the requirements of the particular application.

TELECENTRICITY

Telecentricity determines the amount that magnification changes with object distance. Standard lenses produce images with higher magnification when the object is closer to the lens. We experience this with our eyes. A hand held up near your face looks larger than it does when it is moved farther away. For the same field size, a longer focal length shows less magnification change than a short focal length lens.

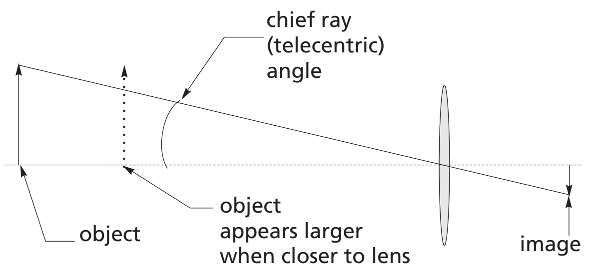
A telecentric lens acts as if it has an infinite focal length. Magnification is independent of object distance. An object moved from far away to near the lens goes into and out of sharp focus, but its image size is constant. This property is very important for gauging three-dimensional objects, or objects whose distance from the lens is not known precisely.

A telecentric lens views the whole field from the same perspective angle. Thus, deep, round holes look round over the entire field instead of appearing elliptical near the edge of the field. Objects at the bottom of deep holes are visible throughout the field.

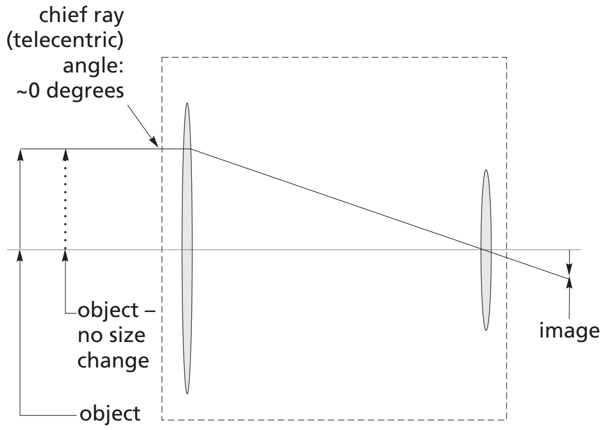
The degree of telecentricity is measured by the chief ray angle in the corner of the field (figure 6.8). In machine vision, a standard commercial lens may have chief ray angles of 10 degrees or more. Telecentric lenses have chief ray angles of less than 0.5 degree, in fact, some telecentric lenses have chief ray angles of less than 0.1 degree.

Telecentricity is a measure of the angle of the chief ray in object space and does not affect the DOF.

DOF is determined by the angles of the marginal rays. Chief ray and marginal ray angles are independent of each other.



(a) conventional camera lens



(b) telecentric lens

Figure 6.8 **Telecentricity: (a) conventional camera (b) telecentric lens**

The objective element of a telecentric lens must be larger than the FOV. The lens must "look straight down" on all portions of the field. Telecentric lenses designed for very large fields are thus large and expensive. Most telecentric lenses cover fields of less than 150 mm in diameter.

GAUGING DEPTH OF FIELD

The gauging depth of field (GDOF) is the range of distances over which the object can be gauged to a given accuracy (figure 6.9). A change in object distance changes the image magnification and therefore the measured lateral position of the object. The GDOF describes how precisely the object distance must be controlled to maintain a given measurement accuracy. Telecentric lenses provide larger GDOFs than do conventional lenses.

DISTORTION

In optics, distortion is a particular lens aberration which causes objects to be imaged farther or closer to the optical axis than for a perfect image. It is a property of the lens design and not the result of manufacturing errors.

Most machine vision lenses have a small amount of pincushion distortion (figure 6.10). Because relative distortion increases as the square of the field, it is important to specify the field over which field distortion is measured.

Distortion is generally specified in relative terms. A lens that exhibits two percent distortion over a given field will image a point in the corner of its field two percent too far from the optical axis. If this distance should be 400 pixels, it will be measured as 408 pixels.

Lens distortion errors are often small enough to ignore. Because distortion is fixed, these errors can also be removed by software calibration. Lenses designed to have low distortion are available.

SPECTRAL RANGE

Most machine vision lenses are color corrected throughout the visible range. Filters that narrow the spectral range to a single color sometimes improve lens resolution. CCD cameras are inherently sensitive to near-infrared (NIR) light. In most cases, an NIR filtershould be included in the system to reduce this sensitivity. In many cameras, the NIR filters are built in.

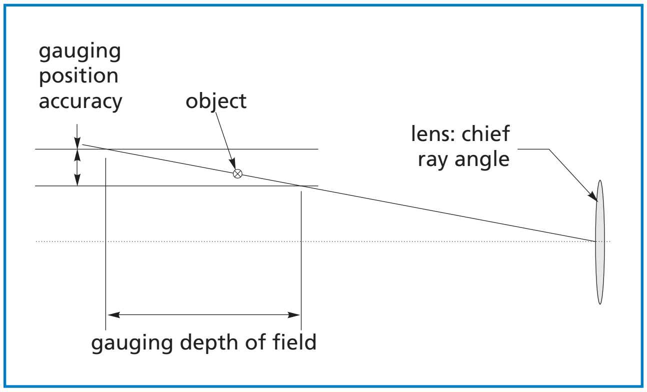


Figure 6.9 **Gauging depth of field**

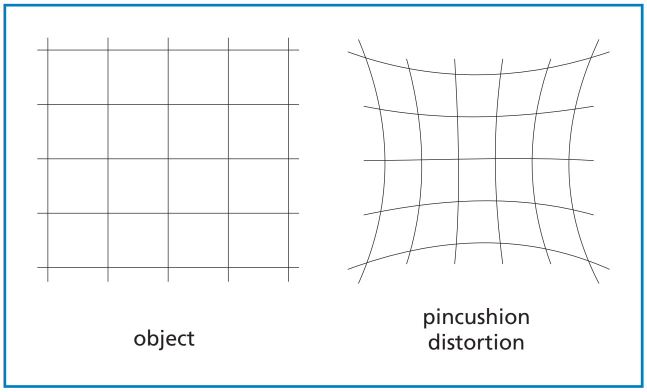


Figure 6.10 **Pincushion distortion**

Microscope Objectives

CHOOSING AN OBJECTIVE

The most important parameter for choosing a microscope objective is its NA. The larger the NA, the higher the resolving power, which means that the objective can distinguish closely spaced features from each other. The NA is related to the magnification; a higher magnification objective usually has a larger NA. The objective provides its specified magnification when used in a microscope with the proper tube length, or with the proper decollimating lens. The objective can also be used at different magnifications; the specified magnification provides an approximate guide. Both NA and magnification are usually printed on the barrel of the objective. An objective with a larger NA gathers more light but provides a smaller DOF, shorter working distance, and higher cost than an objective with a smaller NA. Because these tradeoffs are crucial to the success of the application, the objective NA must be chosen carefully.

The FOV is the sensor size divided by the magnification. The magnification (and FOV) can be adjusted by changing tube length or the focal length of the decollimating lens. Using a magnification greatly different from the one printed on the objective generally results in a poorly optimized system.

Microscope objectives have a small working distance (WD), the distance from the tip of the objective barrel to the object. This is a problem in machine vision, where there are often fixtures that must fit between the objective and the object. For those applications, there are objectives with longer working distance, called LWD or ELWD lenses. These objectives are larger and more expensive than standard objectives.

There are several different and incompatible standards for microscope mounting threads (DIN, JIS, RMS, and others). It is usually not possible to adapt from one thread to another. Within a single family, objectives are usually “parfocal”, which means the distance from the objective mounting flange to the object is the same for each objective in the family. On a microscope, this means the the objective (and magnification) can be switched without a large refocus motion.

TYPES OF OBJECTIVES

Objectives are classified into groups depending on how well they are corrected for the dominant aberrations: chromatic aberration (color), spherical aberration, and field curvature. The simplest objectives (achromats) are corrected for color in the red and blue and for spherical aberration in the green. More complex objectives (apochromats) are color corrected in the red, yellow, and blue and corrected for spherical aberration at two to three different wavelengths. For applications that require good image quality across a wide FOV, “plan” objectives (plan achromats and plan apochromats) are also corrected for field curvature. Plan objectives generally have longer working distances than simple designs.

Each objective is designed to be used with a specific type of microscope. Biological objectives are corrected to view the object through a glass coverslip. If a biological objective, particularly one with a large NA, is used without a coverslip, the image will not be sharp. Similarly, non-biological objectives will not function optimally if there is glass between the objective and the object.

Older microscope objectives (before 1980) were designed to form an image at a given distance (the tube length) behind the objective flange. This distance varied between 160 mm and 210 mm depending on the manufacturer and the application. At the proper tube length, the objectives formed images at their nominal magnifications. Modern microscope objects are "infinity corrected." They are optimized to provide collimated light on their image side. A separate decollimating or tube lens then forms the image. This design gives microscope manufacturers flexibility to insert lighting and beamsplitters in the collimated space behind the objective. The proper focal length tube lens is required to form an image at the objective nominal magnification.

Many special-purpose objectives are available. Some are color corrected for wavelengths in the infrared or ultraviolet regions. Low-fluorescence objectives are available for ultraviolet fluorescence applications. Strain-free objectives are used for applications where the polarization of the image light must be maintained.

Objective Type Designation

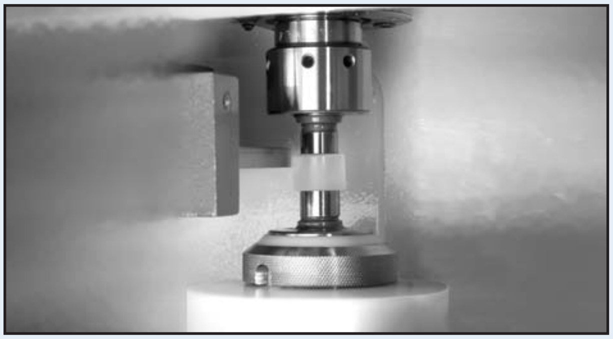
Designation	Meaning	Application
Achro, Achromat	Color corrected at 2 colors, with nominal spherical aberration correction	Low cost, less demanding applications
Fluor, Fl, Fluar, Neofluar, Fluotar	Color and spherical aberration corrected with fluorite element	Intermediate between achro and apo performance
Apo, Apochromat	Color corrected at 3 or more colors, with superior spherical aberration correction	Best polychromatic imaging
EF Achroplan	Extended field (but less than plan)	Wider field than achroplan
Plan, Pl, Achroplan	Corrected for field curvature; wide field of view, longer working distance	Sharp images across the field of view
ELWD SLWD ULWD	Extra-long working distance Super-long working distance Ultra-long working distance	Plan objectives with greatly increased working distances
I, Iris, W/Iris	Includes an iris to adjust numerical aperture	Useful to adjust depth of field and resolution

Ref: Nikon MicroscopyU, http://www.microscopyu.com

Edging and Beveling Systems

The edging and beveling systems at CVI Melles Griot enable us to produce precision lens elements with micron tolerances.

Automated CNC equipment for edging and beveling



Close-up view of CNC centering and edging system

Special Lenses

ZOOM LENSES

Zoom lenses have focal lengths that are adjustable over some range. They are useful for prototypes in which the focal-length requirement has not yet been determined. They can be set at focal lengths between those available with fixed lenses. Zoom lenses are larger, less robust, more expensive, and have smaller apertures than similar fixed-focal-length lenses. Also, they frequently have more distortion.

MACRO LENSES

A camera lens optimized to work at magnifications near 1 is called a macro lens. A macro lens provides better image quality than a standard camera lens used with extension tubes.

TELECENTRIC LENSES

Telecentric lenses provide constant magnification for any object distance (see Telecentricity). They are useful for precision gauging or application where a constant perspective angle across the field is desirable. Their object distance is generally less than that of standard lenses. The magnification of a telecentric lens is fixed by its design. Because the first element must be as large as the field width, telecentric lenses tend to be larger and more expensive than standard lenses.

CLOSE-UP LENSES

Close-up attachment lenses reduce the object distance of a standard lens. The nominal magnification of a lens with a close-focusing attachment is

$$m = \frac{f_{\text{lens}}}{f_{\text{attachment}}} . \qquad (6.14)$$

TELECONVERTERS (EXTENDERS)

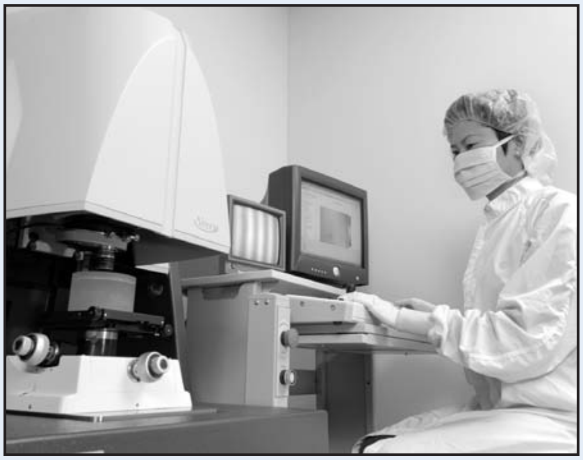
Teleconverters are short relay optics that fit between the lens and the camera and increase the effective lens focal length. They are usually available at 1.5 × and 2 × power. The penalties for their use are increased image-side f-number (by the power factor) and increased distortion.

REVERSE MOUNTING

For magnifications greater than 1, a camera lens can be used in reverse, with the object held at the usual camera plane and the camera in the usual object plane. In this case, the object distance will be short, whereas the lens-to-camera distance is long. Adaptors are available to hold camera lenses in this orientation.

Surface Inspection of Manufactured Lenses

Individual lens elements are inspected for surface defects under bright, oblique-incidence illumination.



Surface roughness measurements are carried out using the latest white-light interferometry and optical profilometry instrumentation.