Fundamentals of Imaging and Machine Vision

6

Introduction and Overview	**6.2**
Choosing a Custom Lens	**6.4**
Creating a Custom Solution	**6.5**
Machine Vision Lens Fundamentals	**6.6**
Machine Vision Lighting Fundamentals	**6.16**
Video Cameras for Machine Vision	**6.20**
Frequently Asked Questions	**6.22**

Introduction and Overview

Today, more and more manufacturers are using machine vision technology to improve productivity and reduce costs. Machine vision integrates optical components with computerized control systems to achieve greater productivity from existing automated manufacturing equipment. At the core of this growth in machine vision are manufacturers' ever-increasing demands for finer control over the quality of manufactured parts. Whether it is the medical industry's desire to reduce liability, or the consumer market's need to lower costs, 100 percent part inspection is becoming the norm. When a single bad part can jeopardize a customer relationship or spur a lawsuit, manufacturers seek to meet quality standards that far exceed the capabilities of older technologies.

Machine vision systems come in many forms. Some systems use an analog camera and digitize the image with a frame grabber. An increasing number of systems use digital cameras which, like any other peripheral device, send data directly to PC memory. For some applications, "smart cameras" provide complete vision systems in a single box. Despite their differences, all these systems depend on the front-end optics to provide a high-quality image to the sensor.

The image is the only source of information for a machine vision system. The quality of the analysis is dependent on the quality of the image, and the quality of the image is determined by the appropriate choice of optics. Software cannot correct for poor image quality. Nonetheless, optics are the most neglected aspect of a vision system.

The lighting and lens must work together to collect the relevant information about the object. The lighting must illuminate each feature, provide good contrast, and minimize confusing artifacts. The lens must resolve features over the entire object and a range of working distances. For alignment and gauging applications, the lens must present the image in a fixed geometry, so that the image location is precisely calibrated to the object's position in space. The lens can image only the rays launched by the lighting; the lighting must launch only rays that contribute to the desired image. The success of the machine vision system depends on the performance of the optics.

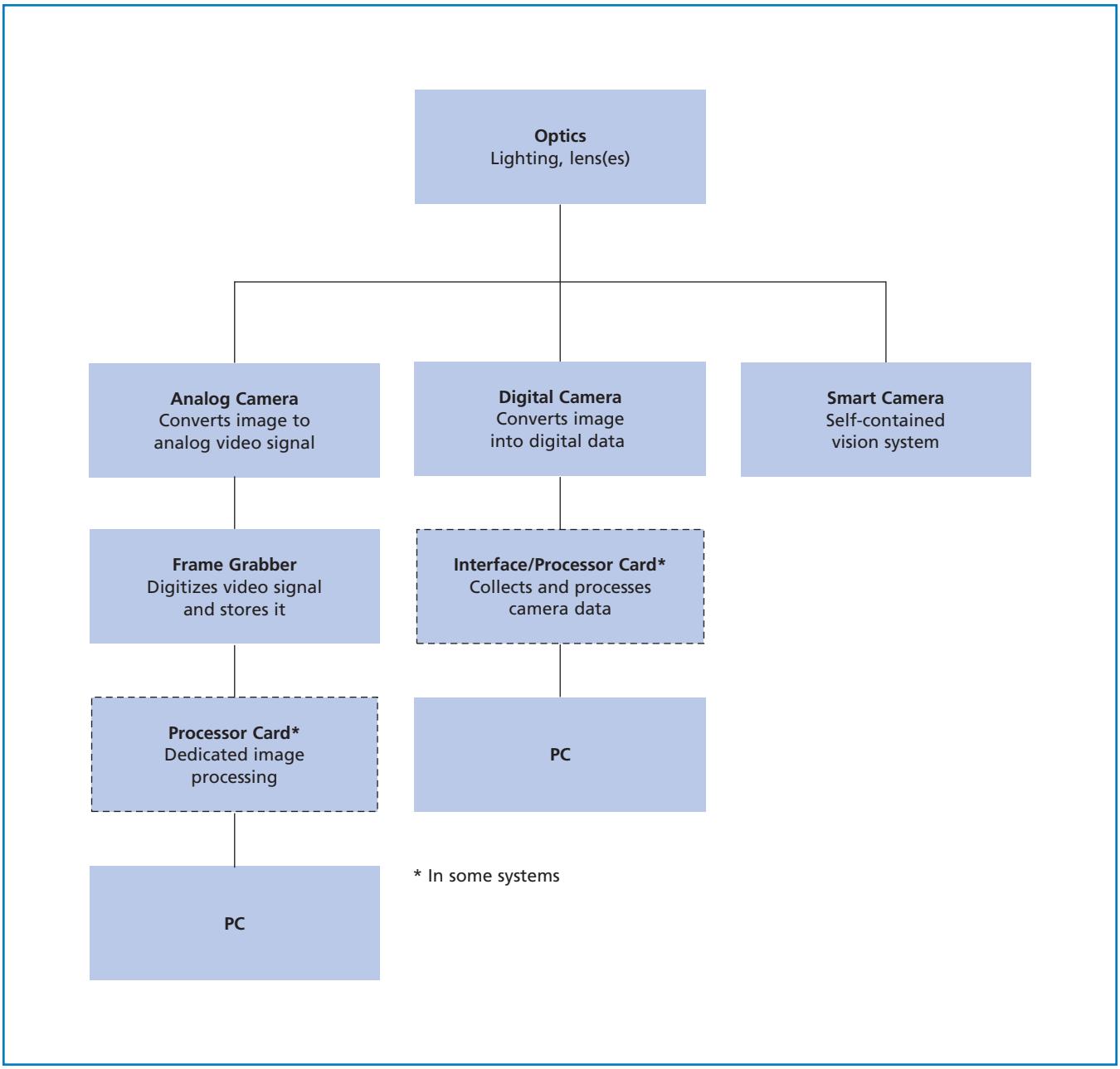
Machine vision continues to expand into new applications. Camera size and cost have decreased. High-resolution digital cameras are in common use. Smart cameras make entire vision systems available for less than the cost of a processor alone only a few years ago. Geometrical pattern matching software has improved the precision and robustness of object location. Each new development leads to new requirements for high-performance optics.

CVI Melles Griot, a leader in optics technology for three decades, is a major resource for professionals in many fields who are working with machine vision systems. Our engineers understand the precision and accuracy required for the most critical components of vision systems — the optics. However complex your requirements, CVI Melles Griot has the expertise and the experience to maximize the power of your machine vision system.

CVI Melles Griot Optics Manufacturing Facilities

CVI Melles Griot manufacturing facility in Rochester, NY, USA.

CVI Melles Griot manufacturing facility in Tamagawa, Japan.



Anatomy of a machine vision system

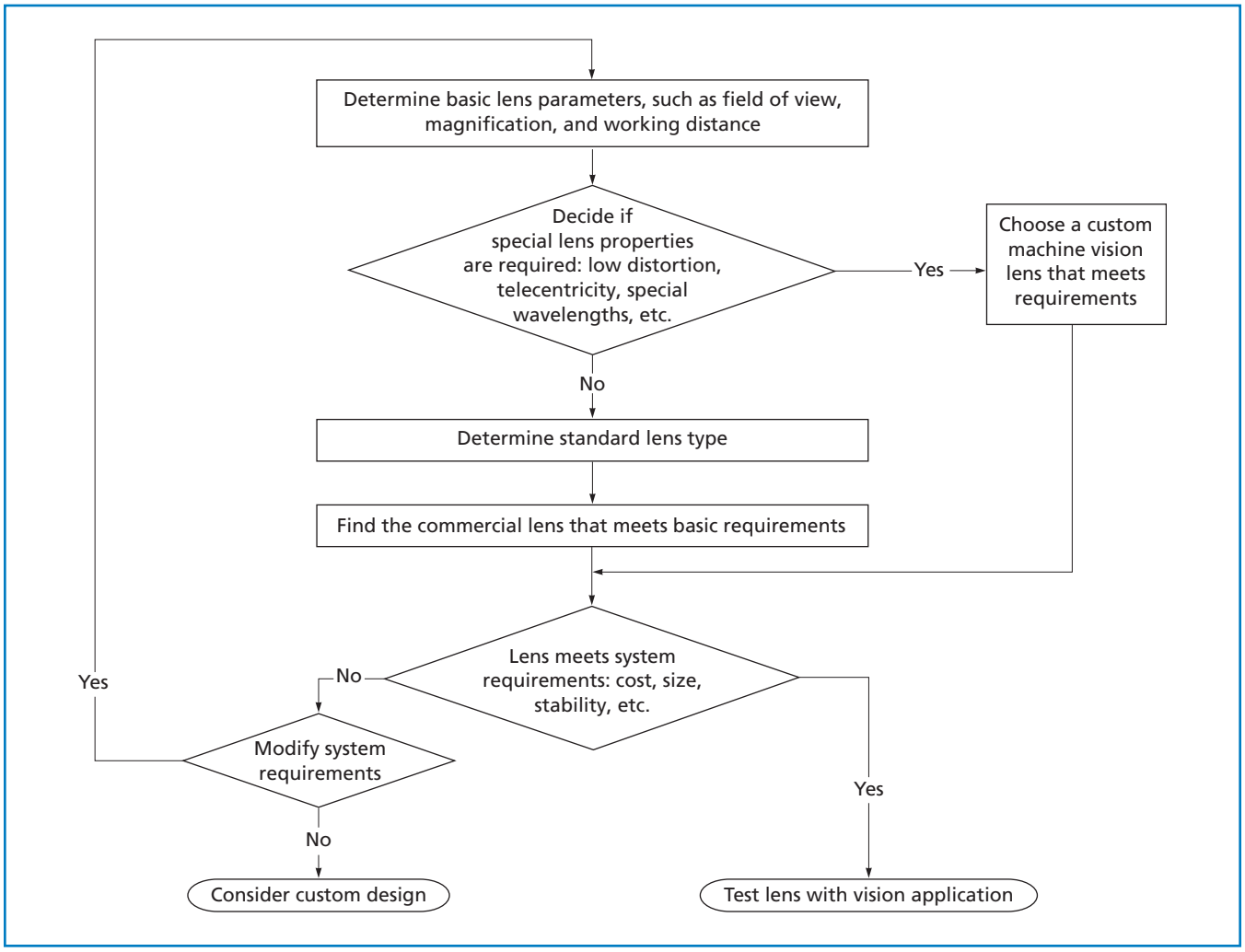
Choosing a Custom Lens

In many cases, the front-end optics for machine vision can be built using off-the-shelf components. Camera, lens, and lighting manufacturers offer a variety of standard products, many of which are specifically designed for machine vision applications. The following pages contain useful information that will help you choose the appropriate components for your front-end optics.

- The field of view required to attain the necessary resolution cannot be achieved using a standard lens.
- The space available is too small to fit a standard lens.
- In addition to precise centering, a change of magnification is required.
- The required depth of field cannot be achieved with a stationary lens.
- The area of interest is not readily accessible with a standard lens.

The decision to design custom front-end optics, especially using a custom lens, should be considered very carefully, because the time and cost can be significant. However, since the lens is critical to system success and custom lenses can provide performance, size, and stability that are not available from standard commercial lenses, the extra expense is often easily justified.

A clear understanding of the system's optical requirements is key to choosing a lens. The figure below can be used to determine whether a custom lens is needed.



Determining the need for a custom lens

Creating a Custom Solution

Successful development of a custom machine vision system requires a partnership between customer and vendor. The customer knows his manufacturing process and requirements. CVI Melles Griot knows how to build production-ready optics. Depending on the application and on customer needs, developing a custom machine vision system includes some or all of the following stages: identification of requirements, a design study, the detailed design, creation of a prototype, and, finally, production. As the following pages demonstrate, CVI Melles Griot works with the customer throughout the development process to achieve the best fit between the optics and the customer's requirements.

IDENTIFICATION OF REQUIREMENTS

The development process begins with the identification of requirements. At this point, CVI Melles Griot takes the widest possible view of the system, including the measurements it is required to make, the environment in which it will work, the systems with which it will interface, the people who will support it, the time available for development, cost targets, and more. Our goal is to develop a solution to the whole problem, not just some of its aspects. It costs far less to deal with conflicts and challenges at this stage than to discover them later. The vision system planning worksheet is one tool we use for this process. We frequently exchange drawings, photographs, or product samples with our customers. In some cases, we visit the customer's site to better understand the requirements.

DESIGN STUDY

Occasionally, we may need to spend significant engineering effort to determine whether we can build a system that meets the requirements. In these cases we propose a design study, which includes calculations, layouts, and lens designs, as well as research into similar systems and available components. We may also test important concepts in the lab. For example, we may make a mock-up of the lighting configuration and make test images of a customer's part to prove that it can be adequately illuminated. The output of a design study is a written report, which serves as a basis for customer review and includes a set of specifications and layouts for the design stage. A principal goal of our custom-system design process is to maximize the probability of success. A design study allows the customer to see our designs and rationale before committing to produce hardware. It also allows CVI Melles Griot to plan the prototype hardware carefully, reducing the technical risk, and enabling us to quote a lower price.

DETAILED DESIGN

During the detailed design phase, we develop a complete drawing package for the optical system. If we have not done a design study, we start by developing complete specifications and a system layout. In either case, we make all glass and metal drawings, assembly drawings, and procedures. At the conclusion of the detailed design, we review the system drawings and final specifications with the customer to ensure the system, as detailed, will meet the requirements.

PROTOTYPE

It is often desirable to build a small number of prototypes of a new system before committing to full production. This allows the customer to test the system in operation and perhaps identify some refinements. It also allows CVI Melles Griot to prove that the design package is correct. We also develop assembly, test, and calibration procedures for the system.

PRODUCTION

CVI Melles Griot produces custom systems in quantities ranging from one to hundreds. During production, we continue to work with the customer to be sure that the system is meeting the requirements.

CVI Melles Griot recognizes that requirements evolve as products and production techniques improve. We are committed to supporting our customers through this evolution with continuing design refinements.

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: .

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

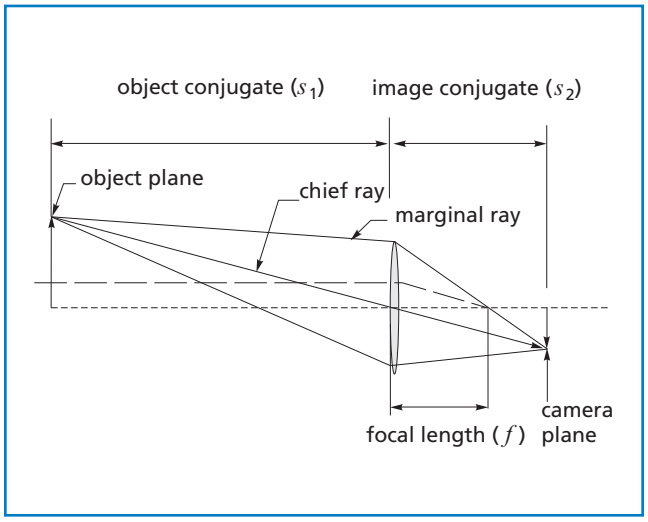


Figure 14.1 **Thin-lens model**

FOCAL LENGTH

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

$$\frac{1}{f} \approx \frac{1}{s_2} \Rightarrow s_2 \approx f \,. \qquad (6.3)$$

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 .

$$m = \frac{s_2}{s_1} \,. \qquad (6.4)$$

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

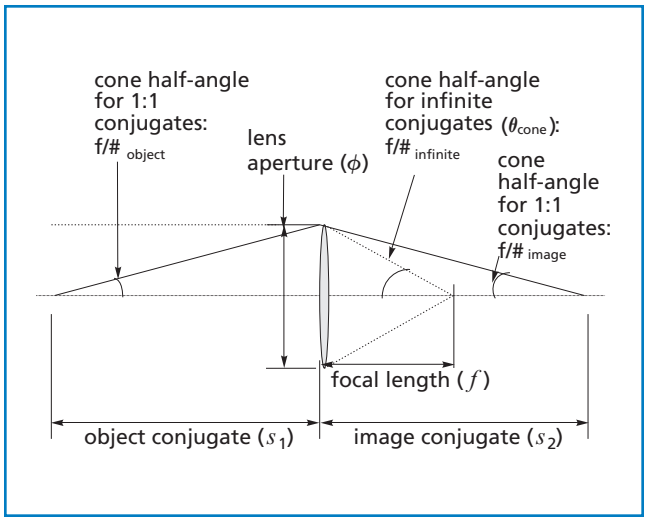


Figure 6.2 **f/number (f/#)**

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

$$\text{f/\#}_\infty = \frac{f}{\phi} \qquad (6.5)$$

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

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

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:

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

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

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

For close objects, $f/\#_{image}$ is larger than $f/\#_{infinity}$, 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

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

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

$$\mathrm{NA} = \sin(\theta_{\mathrm{cone}}). \qquad (6.7)$$

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

$$\mathrm{NA} = \sin\left[\arctan\left(\frac{1}{2 \times f/\#}\right)\right]$$
$$f/\# = \frac{1}{2 \times \tan\left[\arcsin(\mathrm{NA})\right]} \ . \qquad (6.8)$$

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

$$\mathrm{NA} \cong \frac{1}{2 \times f/\#}$$
$$f/\# \cong \frac{1}{2 \times \mathrm{NA}} \ . \qquad (6.9)$$

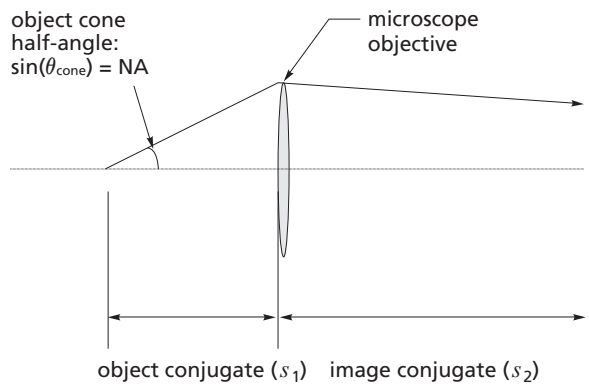


Figure 6.3 **Numerical aperture (NA)**

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.

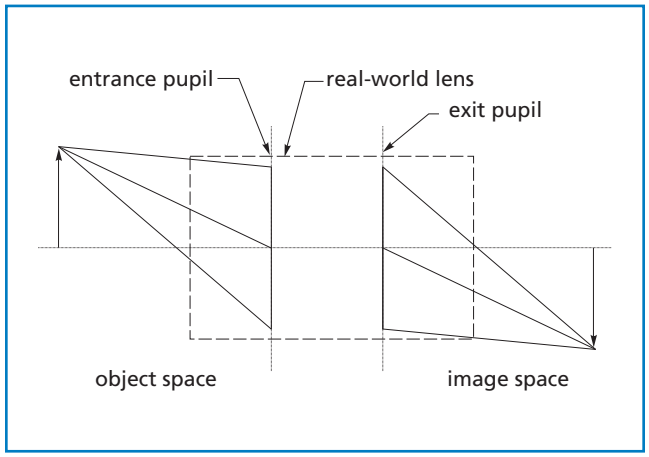


Figure 6.4 **Thick-lens model**

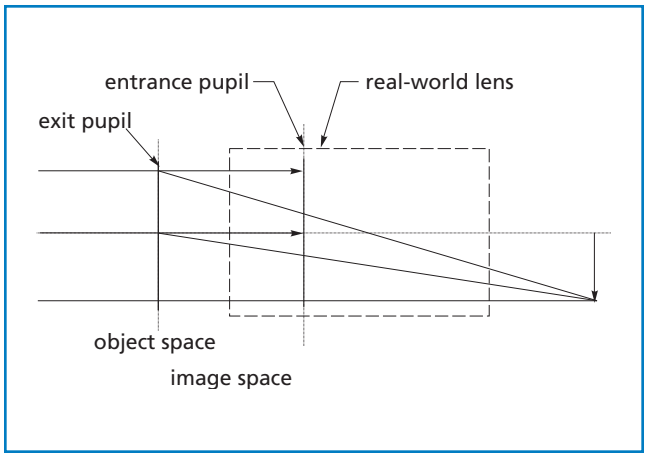


Figure 6.5 **Telephoto lens**

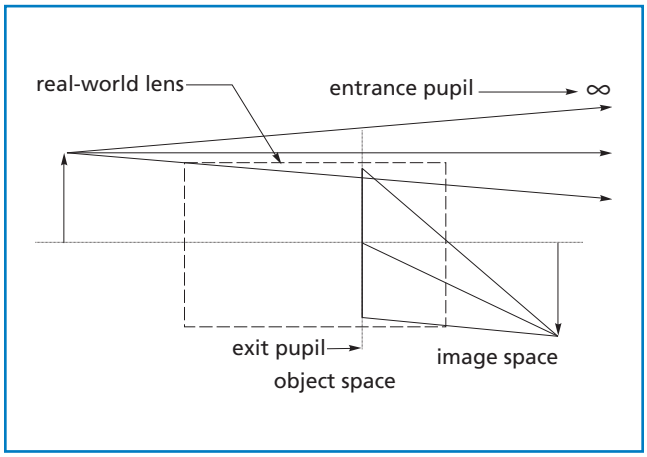


Figure 6.6 **Telecentric lens**

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.

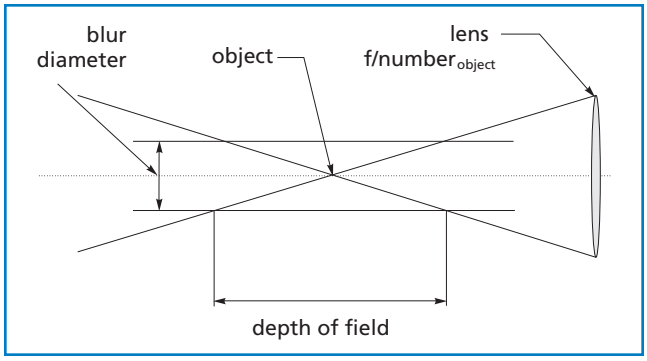


Figure 14.7 **Depth of field**

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:

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

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.

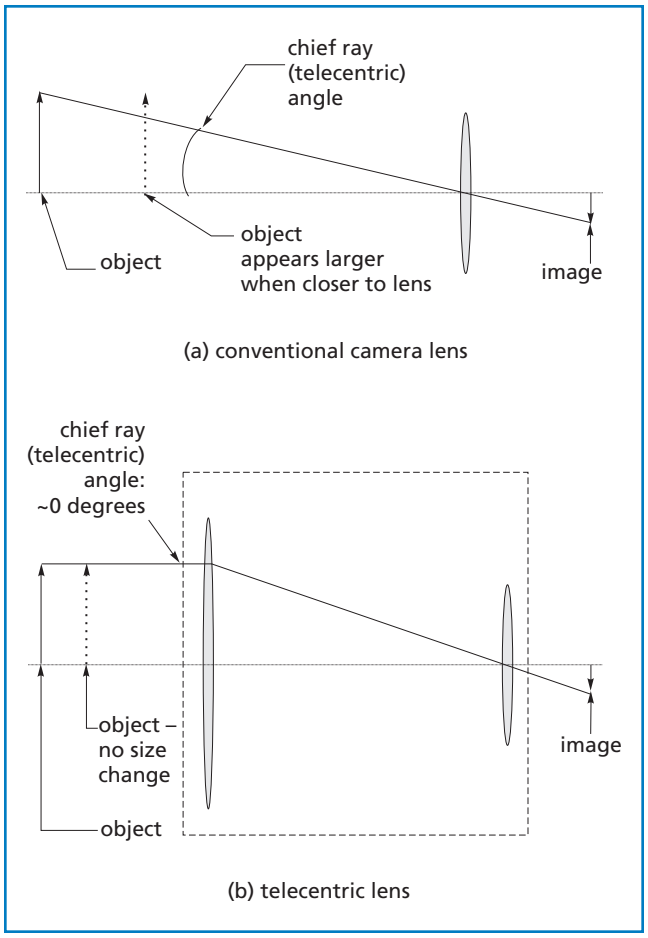


Figure 6.8 **Telecentricity: (a) conventional camera (b) telecentric lens**

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.

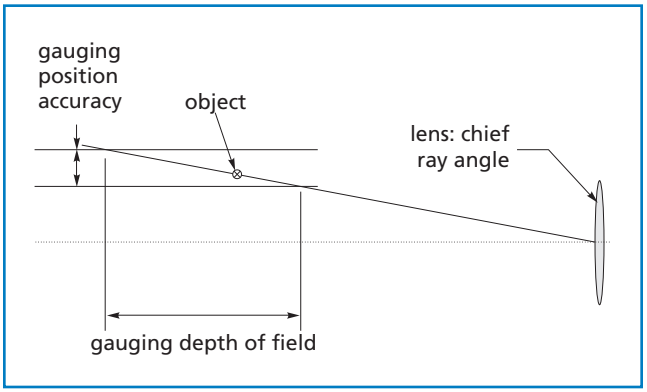


Figure 6.9 **Gauging depth of field**

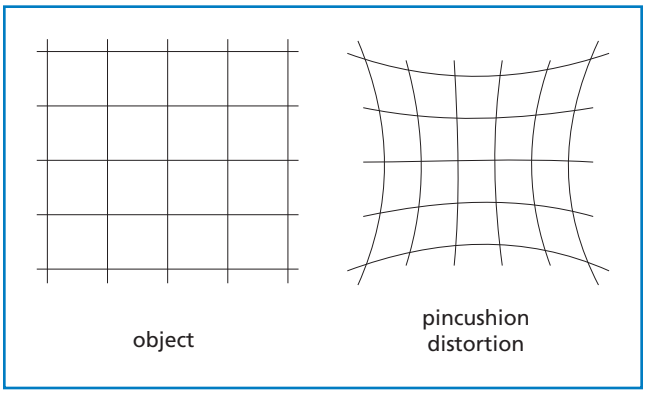


Figure 6.10 **Pincushion distortion**

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

$$m = \frac{f_{\text{lens}}}{f_{\text{attachment}}} \quad . \tag{6.14}$$

TELECONVERTERS (EXTENDERS)

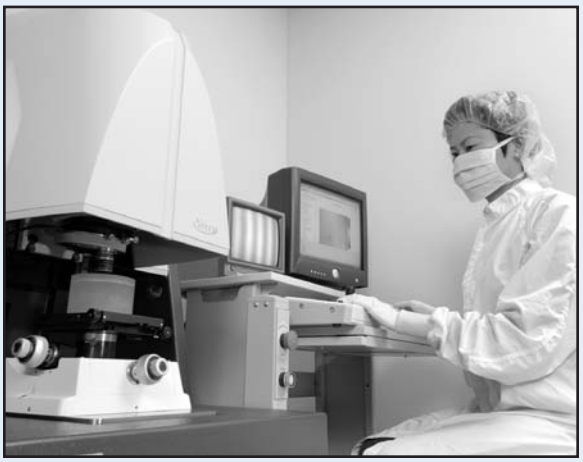
Teleconverters are short relay optics that fit between the lens and the camera and increase the effective lens focal length. They are usually available at 1.5 × and 2 × power. The penalties for their use are increased image-side f-number (by the power factor) and increased distortion.

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.

Machine Vision Lighting Fundamentals

There are well-established design rules for choosing a lens. There are fewer such rules for lighting, yet proper lighting is as important as using the correct lens to form useful images. For a feature to appear in an image, light must come from the illuminator, reflect off the object, and be collected by the lens (figure 6.11). If the light to populate a given ray is not available from the illuminator, that ray will not be part of the image.

In our daily experience, we use light from the environment to see. In machine vision applications, light from the environment is a undesirable, because it may change when we least expect it. We need to provide controlled light in a manner that accentuates features we care about and minimizes distracting features.

Vision lighting and imaging optics are best designed together as a system. The illuminator should launch all rays that can be collected by the lens as part of an image. At the same time, it should not launch rays that will never be part of an image (e.g., those rays that fall outside the FOV of the lens). These extra rays only contribute to glare, which reduces image contrast. Unless the lighting and imaging optics are designed together, it is difficult to achieve a match between them.

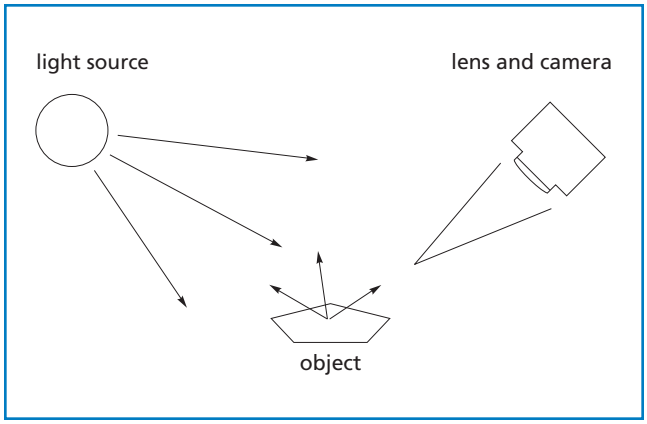


Figure 6.11 **Lighting an object**

Types of Reflection

Objects reflect light in two ways. In specular reflection, light from each incoming ray reflects in a single direction (figure 6.12). A tinned circuit board trace or a mirror exhibits specular reflection. In diffuse reflection, light from each incoming ray is scattered over a range of outgoing angles. A piece of copier paper is a diffuse reflector.

In reality, objects exhibit the whole range of behaviors between the specular and diffuse extremes. A machined metal surface scatters light over a small range of angles, and it scatters differently in directions parallel and perpendicular to the turning marks. Paper exhibits some specular properties, as anyone who has ever tried to read with a high-intensity lamp can attest. Many objects have components that reflect differently. An electrical connector includes both shiny (specular) metal pins and dull (diffuse) plastic housing parts.

SPECULAR REFLECTIONS

Specular reflections are bright but unreliable. They are bright because the intensity of the reflection is comparable to the intensity of the light source. In many cases, a specular reflection saturates the camera. Specular reflections are unreliable because a small change in the angle between the illuminator, the object, and the lens may cause the specular reflection to disappear completely. Unless these angles are well controlled, it is best to avoid depending on specular reflections. The best method for lighting specular parts is with diffuse lighting (figure 6.13). The large illumination solid angle means that the image remains almost constant as the reflection angle changes.

DIFFUSE REFLECTIONS

Diffuse reflections are dim but stable. The intensity of the reflection is reduced from that of the source by a factor of from 10 to 1000. The reflected intensity changes slowly with the angle (figure 6.14). Diffuse surfaces can be lit successfully with either diffuse or point-like illuminators. Other considerations, such as specular elements on the object or the influence of shadows, determine the best approach.

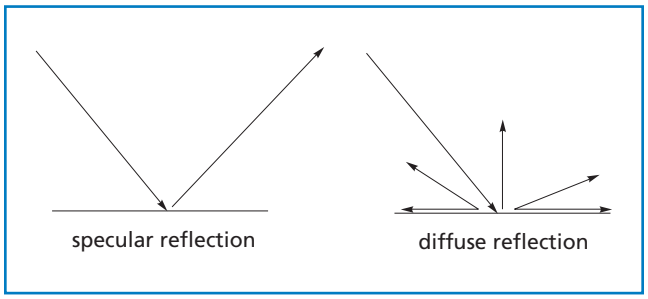


Figure 6.12 **Types of reflection**

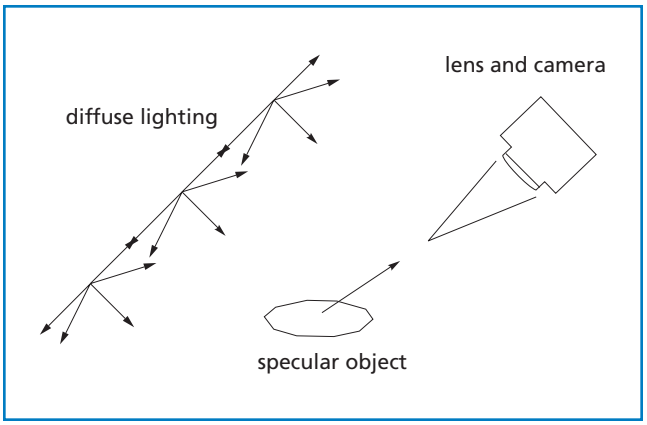


Figure 6.13 **Specular objects viewed with diffuse lighting**

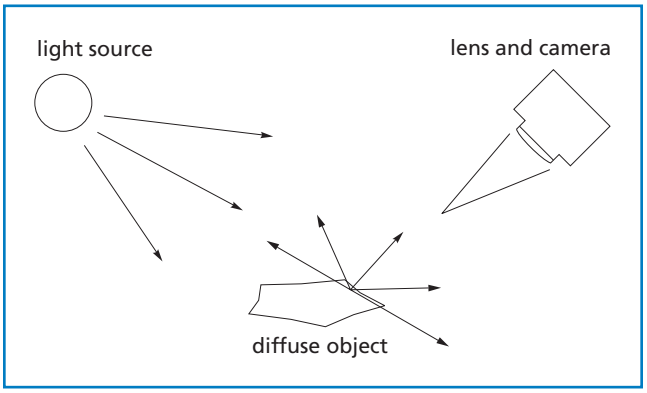


Figure 6.14 **Diffuse objects illuminated with point-like source**

Lenses are cleaned and prepared prior to coating in CVI Melles Griot class 1000 clean-room area.

Lighting Techniques

The basic approach to lighting for a particular application is easily determined. It is a function of the type of object and the features to be measured. The more detailed lighting design builds on this basic technique. For examples, see the accompanying table.

LIGHTING SOLID ANGLE: POINT OR DIFFUSE

Lighting solid angle is the area of a unit sphere, centered on the object, that the illumination occupies (figure 6.15). Just as angles are measured in radians, with 2π radians in a full circle, solid angles are measured in steradians, with 4π steradians in a full sphere. Illumination from a small solid angle is called point-like; illumination from a large solid angle is called diffuse.

POINT-LIKE LIGHTING

Point-like lighting is generally easy to implement because the illuminators are small and can be located at a distance from the object. Incandescent lamps, optical fiber bundles, ring lights, and LEDs are examples of point-like illuminators. Some, like fiber optic bundles, are directional, so light can be directed onto the object from a distance.

Point-like illumination provides high intensity and light efficiency. It is good for creating sharp image edges, casting shadows, and accenting surface features. Their small size makes the illuminators easier to mount and integrate than diffuse sources.

The same shadows and surface features that are useful in some applications can be distractions in others. With specular objects, point-like illumination creates very bright reflections which may saturate video cameras. Away from these reflections, specular objects appear dark.

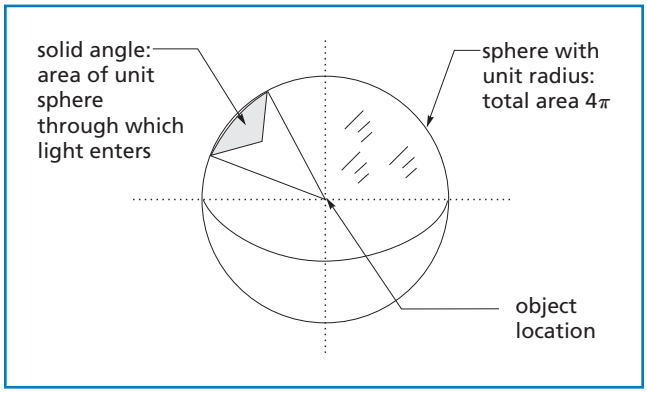


Figure 6.15 **Solid angle**

Comparison Table for Different Lighting Techniques

Illumination	Solid Angle	Direction	Advantages	Disadvantages
Directional Front Illumination Incandescent lamp or fiber bundle illuminates object from the top	Point	Front	Easy to implement; good for casting shadows; fiber-optic delivery available in many configurations	May create unwanted shadows; illumination is uneven
Coaxial Lighting Illumination from the precise direction of the imaging lens, either through the lens or with a beamsplitter in front of the lens	Point	Front	Eliminates shadows; uniform across field of view	Complicated to implement; intense reflection from specular surfaces
Diffuse Front Illumination Fluorescent lamp, fiber illuminator with diffuser, or incandescent lamp with diffuser; illuminates object from the front	Diffuse	Front	Soft, relatively nondirectional; reduces glare on specular surfaces; relatively easy to implement	Illuminator relatively large; edges of parts may be fuzzy; low contrast on monocolor parts
Light Tent Diffuse illuminator surrounds object	Diffuse	Front	Eliminates glare; eliminates shadows	Must surround object; illuminator is large; can be costly
Dark-Field Illumination Point-like source at near right angle to object surface	Point	Side	Illuminates defects; provides a high-contrast image in some applications	Does not illuminate flat, smooth surfaces
Diffuse Backlighting Source with diffuser behind object	Diffuse	Back	Easy to implement; creates silhouette of part; very-high-contrast image; low cost	Edges of parts may be fuzzy; must have space available behind object for illuminator
Collimated Backlighting Point source with collimating lens behind object	Point	Back	Produces sharp edges for gauging	Must have space available behind object for illuminator
Polarized Front Illumination Point-like or diffuse front illumination; polarizer on illuminator; analyzer in front of imaging lens	Point or diffuse	Front	Reduces glare	Reduces light to lens
Polarized Backlighting Diffuse backlight; polarizer on illuminator; analyzer in front of imaging lens	Diffuse	Back	Highlights birefringent defects; relatively easy to implement	Only useful for birefringent defects; edges of parts may be fuzzy; must have space available behind object for illuminator

DIFFUSE LIGHTING

By definition, diffuse lighting must cover a large solid angle around the object. Fluorescent lamps (both straight tubes and ring lights) are inherently diffuse. Diffusers in front of point-like sources make them more diffuse.

Diffuse illumination of specular surfaces allows imaging without bright reflections. Surface texture is minimized, and there is less sensitivity to surface angles on parts.

Diffuse illumination can be difficult to implement, because the illuminator must surround much of the object. For example, when reading characters stamped on textured foil, sources with solid angles approaching 2π steradians are required. These "light tents" are difficult to construct effectively because the lens, camera, and handling equipment must be mounted around the illuminator. Diffuse illumination can also cause blurred edges in images. In general, a diffuse illuminator is more complex than a point-like illuminator.

LIGHTING DIRECTION—BRIGHT FIELD

In bright-field illumination, the light comes in approximately perpendicular to the object surface (figure 6.16). The whole object appears bright, with features displayed as a continuum of gray levels. Normal room lighting is bright-field illumination. This sort of illumination is used for most general-vision applications.

An important special case of bright-field illumination is coaxial illumination. Here, the object is illuminated from precisely the direction of the imaging

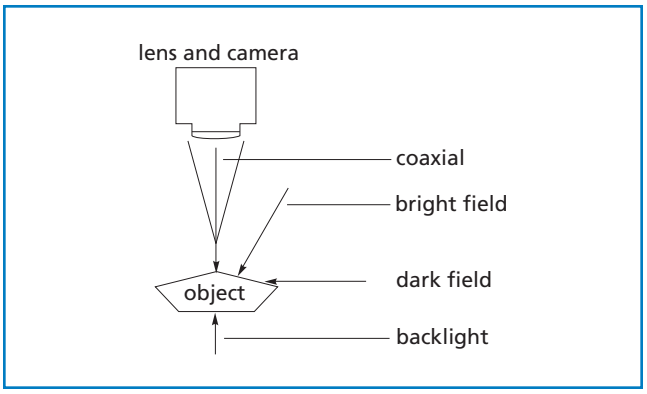


Figure 6.16 **Lighting angles**

lens. This requires a beamsplitter, either within or in front of the imaging lens. Coaxial illumination is used to inspect features on flat, specular surfaces, to image within deep features, and to eliminate shadows.

LIGHTING DIRECTION—DARK FIELD

If the object is illuminated from a point parallel to its surface, texture and other high-angle features appear bright while most of the object appears dark. This low-angle illumination is called dark-field illumination. Dark-field illumination is useful for imaging surface contamination, scratches, and other small raised features.

LIGHTING DIRECTION—BACKLIGHT

Backlight illumination means the illuminator is behind the object. It can be either point-like or diffuse. Point-like lighting, projected through a collimator whose axis is parallel to the lens axis, is similar to coaxial lighting. There are two distinct uses of backlighting: viewing translucent objects in transmission and silhouetting opaque objects.

Sheet glass is an example of a translucent product that is inspected by using backlight. Point-like lighting that is not coaxial with the lens highlights surface defects (scratches, gouges) as well as internal defects (bubbles, inclusions).

Backlighting is more commonly used to silhouette opaque parts. Silhouettes are easy images to process because they are inherently two dimensional and binary. Flexible parts feeders frequently use backlighted images to determine the orientation of mechanical parts to be picked up by a robot for assembly.

LIGHTING COLOR

Most machine vision applications use unfiltered light; however, in some cases, monochromatic illumination provides better feature contrast. A narrow spectrum also reduces the effect of any chromatic aberration in the imaging lens and therefore provides improved resolution. Filtering does, however, reduce the amount of illumination and may be unsuitable for applications in which there is a shortage of light.

POLARIZATION

Polarized illumination is used to reduce glare from specular surfaces. A polarizer is placed in front of the illuminator, and another polarizer (called the analyzer), whose polarization axis is perpendicular to that of the first, is placed in front of the imaging lens. Light that is specularly reflected from the object retains its polarization direction and is therefore blocked by the analyzer. Light scattered from the object is randomly polarized and is passed by the analyzer.

LIGHT SOURCES

Several types of light sources and illuminators are available for machine vision applications; their properties are summarized in the accompanying table.

Advantages and Disadvantages of Different Light Sources

Light Source Type	Advantages	Disadvantages
LED Array of light-emitting diodes	Can form many configurations within the arrays; single color source can be useful in some applications; can strobe LEDs at high power and speed	Some features hard to see with single color source; large array required to light large area
Fiber-Optic Illuminators Incandescent lamp in housing; light carried by optical fiber bundle to application	Fiber bundles available in many configurations; heat and electrical power remote from application; easy access for lamp replacement	Incandescent lamp has low efficiency, especially for blue light
Fluorescent High-frequency tube or ring lamp	Diffuse source; wide or narrow spectral range available; lamps are efficient and long lived	Limited range of configurations; intensity control not available on some lamps
Strobe Xenon arc strobe lamp, with either direct or fiber bundle light delivery	Freezes rapidly moving parts; high peak illumination intensity	Requires precise timing of light source and image capture electronics; may require eye protection for persons working near the application

Video Cameras for Machine Vision

Many cameras are available for machine vision. They incorporate different sensors and different interface electronics, and they come in many sizes. Together, the camera and lens determine the FOV, resolution, and other properties of the image. Many cameras are designed specifically for machine vision applications. This section outlines key issues that should be addressed when choosing a camera lens—particularly those that also affect the choice of a lens.

Camera Types

SENSORS

Most machine vision cameras use charge-coupled device (CCD) image sensors. Charge from each line of pixels is transferred down the line, pixel by pixel and row by row, to an amplifier where the video signal is formed. CCD cameras are available in a wide variety of formats, resolutions, and sensitivities. They provide the best performance for most applications.

Complementary metal-oxide semiconductor (CMOS) sensors are becoming available for some applications. Because they are made using the same processes used to fabricate computer chips, they can be produced very inexpensively. Low-cost CMOS cameras are already used in toys and in webcams. Unlike CCD sensors, which must be read out one full line at a time, CMOS sensors can be read pixel by pixel, in any order. This is useful for time-critical applications in which only part of the image is of interest. At present, the noise performance of CMOS sensors is inferior to that of CCDs.

INTERFACES

Two types of camera interfaces are in use: analog and digital. In an analog camera, the signal from the sensor is turned into an analog voltage and sent to the frame-grabber board in the vision-system computer. EIA, RS-170, NTSC, CCIR, and PAL are all common analog interface standards. Analog cameras are inexpensive, but they are subject to noise and timing problems.

Most new machine vision cameras use a digital interface. The signal from each pixel is digitized by the camera, and the data are sent in digital form directly to the computer. CameraLink® and Firewire® are two popular digital interface standards. The digital signal is not subject to noise, and there is a perfect correspondence between each pixel on the sensor and in the image. Digital cameras support a wide variety of image resolutions and frame rates. Since the signal is already digitized, a simple interface board replaces the frame-grabber.

REMOTE-HEAD CAMERAS

Machine vision cameras are now quite compact; many are smaller than 50-mm cubes. Remote-head cameras have an even smaller camera "head" consisting of the sensor chip in a protective enclosure, connected to the camera body by a short (<1 m) length of cable. Microhead or "lipstick" cameras can be very small, but they are also much more expensive than single-piece cameras.

COLOR CAMERAS

Most color CCD cameras use a single sensor with an array of color filters printed over their pixels. Adjacent pixels sense different colors, so the resolution at each color is lower than that of a similar monochrome sensor. Some high-performance cameras use a color-separation prism to send light to three separate CCDs. These cameras provide full resolution at each color. Lenses for these "three-chip" cameras must have sufficient back working distance to allow room for the prism.

LINE-SCAN CAMERAS

Line-scan cameras have a single row of pixels, 1000, 2000, 4000, or more pixels long. They record images one row at a time. Often the object moves past the camera to provide the second dimension (e.g., a web of paper being inspected during manufacture). Line-scan cameras provide high-resolution images at very high data rates. Long line-scan sensors require large-format lenses to cover their length. In addition, because each line of pixels is exposed for only a very short time, line-scan cameras require intense lighting and large-aperture lenses.

CAMERA FORMATS

The size of an image sensor is called its format (figure 6.17). The name of a format does not correspond to any dimension. Historically, a ½-inch format is the size of the sensing area of a vidicon tube, which is ½ inch in diameter. It is important to choose a lens that covers the camera format. For a given FOV, the camera format determines the required magnification. A larger sensor requires a larger magnification for a given FOV.

CameraLink® is a registered trademark of Automated Imaging Association (AIA).
Firewire® is a registered trademark of Apple Computer, Inc.

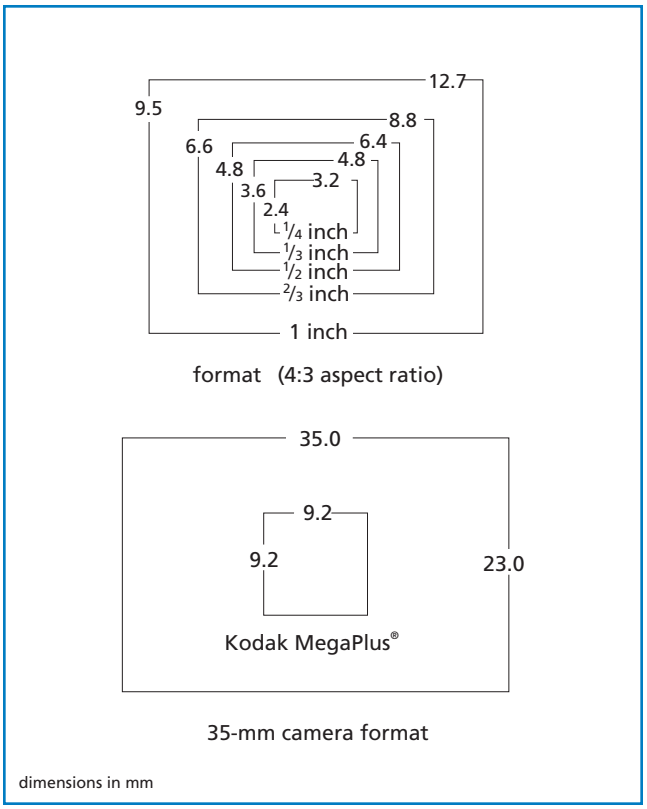


Figure 6.17 **Camera formats**

Lenses for High-Resolution Cameras

To improve sensitivity, many high-resolution CCD sensors include microlens arrays on their surfaces. These arrays make the active area of the pixels appear larger, so that the active-area fraction (fill factor) appears to be near 100 percent. Unfortunately, this is true only for light that is nearly normal to the sensor surface. Light reaching the sensor at greater angles (e.g., >5 deg) misses the active area and is lost. This means that lenses used with these sensors must have a long exit-pupil distance and should not have a very small f-number; otherwise the edges of the image will appear dark.

Frequently Asked Questions

Why are custom lenses so much more expensive than lenses from stock?

A: The cost of manufacturing optics is extremely volume dependent. Mass-produced lenses provide excellent performance at low cost. Lenses produced in small quantity can cost five to twenty times as much. It is always worth attempting to use or adapt a mass-produced lens for an application before designing a custom lens.

How can I prevent my vision optics from moving out of adjustment?

A: Optical mounts for on-line applications should be rigid, have positive locks, and have no more than the required adjustments. Laboratory mounting fixtures are generally not rugged enough for permanent on-line installations.

How should I mount my video camera and lens?

A: Machine vision optics should be mounted firmly but not stressed by excessive force. Do not rely on the camera C-mount thread to support heavy lenses. Either mount the lens and let the camera be supported by the lens, or provide support for both. Avoid overtightening the lens mounting clamps.

How can I increase the DOF of my lens?

A: Increase the f-number (decrease the aperture size). This may require increased lighting. However, very large f-numbers (>f/22 image side working f-number) will significantly degrade the lens resolution.

Do telecentric lenses have larger DOFs than other lenses?

A: No. The image from a telecentric lens remains in focus over the same DOF as that of a conventional lens working at the same f-number. Telecentric lenses provide constant magnification at any object distance. Therefore, they make accurate dimensional measurements over a larger range of object distances than a conventional lens.

Do telecentric lenses have less distortion than other lenses?

A: In optics, "distortion" is the name of a specific aberration inherent in lens designs. Telecentric lenses offered by CVI Melles Griot have low distortion. Low distortion and telecentricity are separate, unrelated lens parameters.

Can I change the magnification of my telecentric lens?

A: No. By definition, a telecentric lens has a fixed magnification. CVI Melles Griot offers a variety of telecentric lenses with a large selection of magnifications.

Is there a telecentric lens with a very large FOV?

A: Because the first element of a telecentric lens must be larger than its FOV, telecentric lenses are generally restricted to fields of less than 150 mm. Larger FOVs are possible in some applications, including web inspection, using line-scan cameras.

CVI Melles Griot Optical Systems

The two photos shown below are examples of optical systems designed and manufactured by the CVI Melles Griot manufacturing facility in Japan.

CVI Melles Griot developed this high-performance projection lens for use in semiconductor manufacturing equipment.

CVI Melles Griot designed and manufactured this MegaVision™ ultrawide FOV HDTV lens with an aspect ratio of 48:9.

OEM and Special Coatings

CVI Melles Griot maintains advanced coating capabilities. In the last few years, CVI Melles Griot has expanded and improved these coating facilities to take advantage of the latest developments in thin-film technology. The resulting operations can provide high-volume coatings at competitive prices to OEM customers, as well as specialized, high-performance coatings for the most demanding user. The most important aspect of our coating capabilities is our expert design and manufacturing staff. This group blends years of practical experience with recent academic research knowledge. With a thorough understanding of both design and production issues, CVI Melles Griot excels at producing repeatable, high-quality coatings at competitive prices.

USER-SUPPLIED SUBSTRATES

CVI Melles Griot not only coats catalog and custom optics with standard and special coatings but also applies these coatings to user-supplied substrates. A significant portion of our coating business involves applying standard or slightly modified catalog coatings to special substrates.

HIGH VOLUME

The high-volume output capabilities of the CVI Melles Griot coating departments result in very competitive pricing for large-volume special orders. Even the small-order customer benefits from this large volume. Small quantities of special substrates can be cost-effectively coated with popular catalog coatings during routine production runs.

CUSTOM DESIGNS

A large portion of the work done at the CVI Melles Griot coating facilities involves special coatings designed and manufactured to customer specifications. These designs cover a wide range of wavelengths, from the infrared to deep ultraviolet, and applications ranging from basic research through the design and manufacture of industrial and medical products. The most common special coating requests are for modified catalog coatings, which usually involve a simple shift in the design wavelength.

TECHNICAL SUPPORT

Expert CVI Melles Griot applications engineers are available to discuss your system requirements. Often a simple modification to a system design can enable catalog components or coatings to be substituted for special designs at a reduced cost, without affecting performance.

Laser-Induced Damage

CVI Melles Griot conducts laser-induced damage testing of our optics. Although our damage thresholds do not constitute a performance guarantee, they are representative of the damage resistance of our coatings. Occasionally, in the damage-threshold specifications, a reference is made to another coating because a suitable high-power laser is not available to test the coating within its design wavelength range. The damage threshold of the referenced coating should be an accurate representation of the coating in question.

For each damage-threshold specification, the information given is the peak fluence (energy per square centimeter), pulse width, peak irradiance (power per square centimeter), and test wavelength. The peak fluence is the total energy per pulse, the pulse width is the full width at half maximum (FWHM), and the test wavelength is the wavelength of the laser used to incur the damage. The peak irradiance is the energy of each pulse divided by the effective pulse length, which is from 12.5 to 25 percent longer than the pulse FWHM. All tests are performed at a repetition rate of 20 Hz for 10 seconds at each test point. This is important because longer durations can cause damage at lower fluence levels, even at the same repetition rate.

The damage resistance of any coating depends on substrate, wavelength, and pulse duration. Improper handling and cleaning can also reduce the damage resistance of a coating, as can the environment in which the optic is used. These damage threshold values are presented as guidelines and no warranty is implied.

When choosing a coating for its power-handling capabilities, some simple guidelines can be followed to make the decision process easier. First, the substrate material is very important. Higher damage thresholds can be achieved using fused silica instead of BK7. Second, consider the coating. Metal coatings have the lowest damage thresholds. Broadband dielectric coatings, such as the HEBBAR™ and MAXBRIte™ are better, but single-wavelength or laser-line coatings, such as the V coatings and the MAX-R™ coatings, are better still. If even higher thresholds are needed, then high-energy laser (HEL) coatings are required. If you have any questions or concerns regarding the damage levels involved in your applications, please contact a CVI Melles Griot applications engineer.

Leybold SYRUSpro™ PIAD Coating System

Our Leybold SYRUSpro™ plasma ion-assisted deposition (PIAD) coating system features an advanced plasma source (APS) composed of a hot cathode, a cylindrical anode tube, and a solenoid magnet. During operation, the plasma system is energized by applying a dc voltage between the large heated cathode and surrounding anode. The dc voltage between the cathode and anode creates a glow discharge plasma, which is supplied with a noble gas such as argon. The energetic plasma is extracted in the direction of the substrate holder and fills the evaporation chamber. A high flux of energetic ions bombard the growing thin film increasing the packing density of the condensed molecules via momentum transfer. Simultaneously, electrons in the plasma provide an effective source of charge neutralization allowing excellent plasma process uniformity through the chamber. To ensure the growth of fully stoichiometric films, reactive gasses such as oxygen can be introduced in the plasma facilitating film growth rates as high as 1.5 nm/sec depending upon the evaporant material. Expert use of the PIAD process allows fine control of packing density, stoichiometry, refractive index, and film stress. Unlike conventionally coated substrates, PIAD can produce thin films that are highly insensitive to changes in environmental humidity levels and temperature.

The Leybold SYRUSpro coating system's advanced optical monitoring system works in conjunction with a redundant quartz-crystal thickness-measurement system to enable complex multiwavelength monitoring strategies, trigger-point control (non-quarter wavelength layers), and multiple redundant test or witness sample strategies. In quartz-crystal film-thickness monitoring systems, deposition rate is based upon the measurement of the changing frequency of oscillation of a natural quartz crystal as the accumulating evaporated thin-film increases the crystal's mass, changing its natural frequency (oscillation frequency decreases as the film thickness increases). This changing frequency is typically monitored every 100 msec, providing the utmost in accuracy and product-to-product coating uniformity.

SYRUS*pro*™ coater