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.

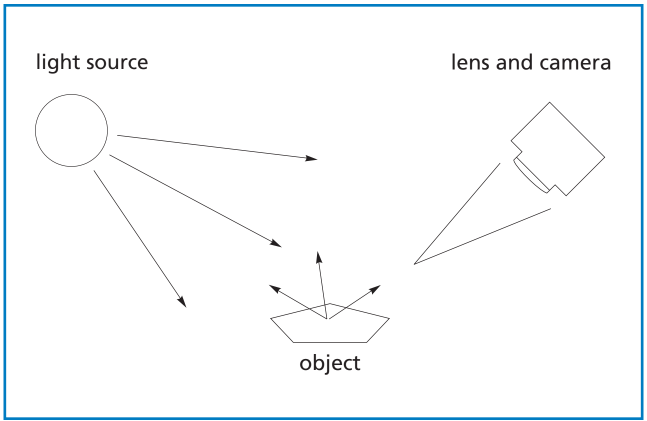

Figure 6.11 **Lighting an object**

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.

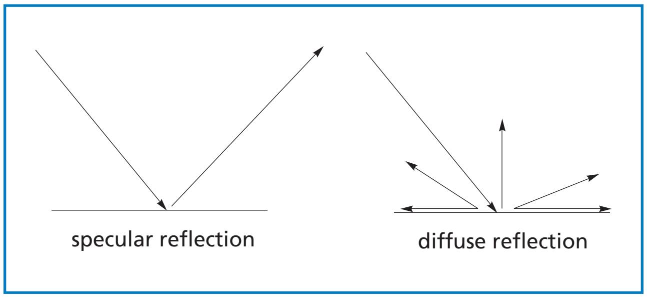

Figure 6.12 **Types of reflection**

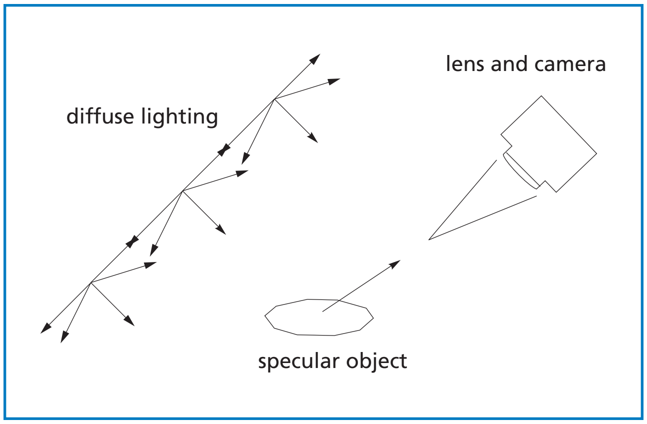

Figure 6.13 **Specular objects viewed with diffuse lighting**

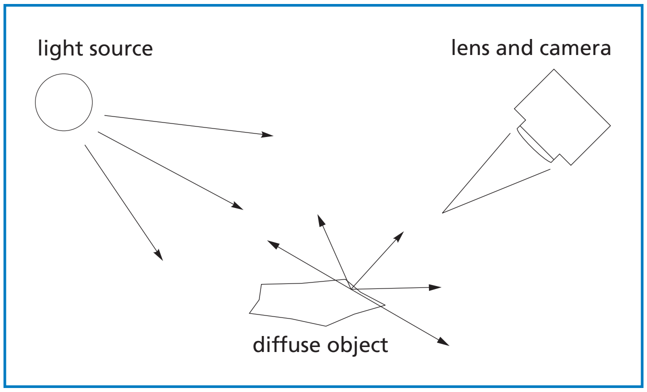

Figure 6.14 **Diffuse objects illuminated with point-like source**

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.

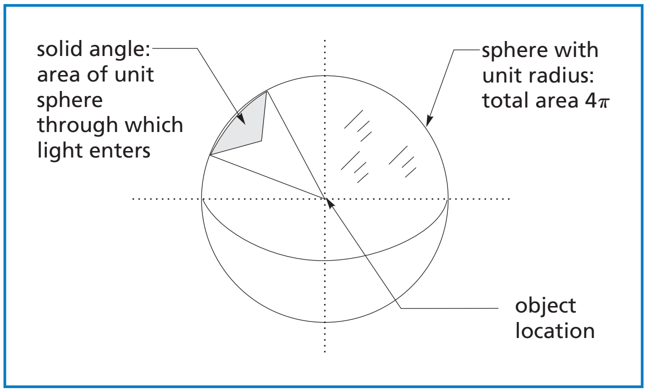

Figure 6.15 **Solid angle**

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

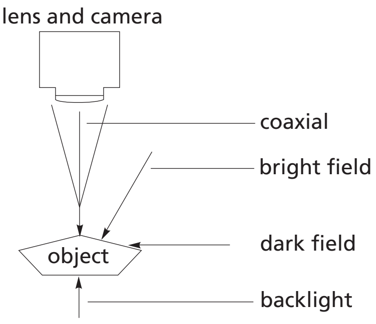

Figure 6.16 **Lighting angles**

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