Opto Engineering®

Basics
# Summary

## Optics
- **Introduction**
- **Optics basics**
- **Image quality**
- **Lens types**

## Lighting
- **Introduction**
- **Light in machine vision**
- **LED illumination**
- **Illumination geometries and techniques**
- **Wavelength and optical performance**
- **Structured illumination**
- **Illumination safety and class risks of LEDs according to EN62471**

## Cameras
- **Introduction**
- **Camera types**
- **Sensor and camera features**
- **Digital camera interfaces**

## Vision systems
- **Introduction**
- **Applications**
- **Types of vision systems**
- **How a vision system works**
The basic purpose of a lens of any kind is to collect the light scattered by an object and recreate an image of the object on a light-sensitive 'sensor' (usually CCD or CMOS based). A certain number of parameters must be considered when choosing optics, depending on the area that must be imaged (field of view), the thickness of the object or features of interest (depth of field), the lens to object distance (working distance), the intensity of light, the optics type (telecentric/entocentric/pericentric), etc.

The following list includes the fundamental parameters that must be evaluated in optics:

- **Field of View (FoV)**: total area that can be viewed by the lens and imaged onto the camera sensor.
- **Working distance (WD)**: object to lens distance where the image is at its sharpest focus.
- **Depth of Field (DoF)**: maximum range where the object appears to be in acceptable focus.
- **Sensor size**: size of the camera sensor’s active area. This can be easily calculated by multiplying the pixel size by the sensor resolution (number of active pixels in the x and y direction).
- **Magnification**: ratio between sensor size and FoV.
- **Resolution**: minimum distance between two points that can still be distinguished as separate points. Resolution is a complex parameter, which depends primarily on the lens and camera resolution.
Optics basics

Lens approximations and equations

The main features of most optical systems can be calculated with a few parameters, provided that some approximation is accepted. The paraxial approximation requires that only rays entering the optical system at small angles with respect to the optical axis are taken into account. The thin lens approximation requires the lens thickness to be considerably smaller than the radii of curvature of the lens surfaces: it is thus possible to ignore optical effects due to the real thickness of the lenses and to simplify ray tracing calculations. Furthermore, assuming that both object and image space are in the same medium (e.g. air), we get the fundamental equation:

\[
\frac{1}{s} - \frac{1}{s'} = \frac{1}{f}
\]

where \(s\) (\(s'\)) is the object (image) position with respect to the lens, customarily designated by a negative (positive) value, and \(f\) is the focal length of the optical system (cf. Fig. 1). The distance from the object to the front lens is called working distance, while the distance from the rear lens to the sensor is called back focal distance. Henceforth, we will be presenting some useful concepts and formulas based on this simplified model, unless otherwise stated.

Camera mounts

Different mechanical mounting systems are used to connect a lens to a camera, ensuring both good focus and image stability. The mount is defined by the mechanical depth of the mechanics (flange focal distance), along with its diameter and thread pitch (if present). It’s important that the lens flange focal distance and the camera mount flange distance are exactly the same, or focusing issues may arise. The presence of a threaded mechanism allows some adjustment to the back focal distance, if needed. For example, in the Opto Engineering® PCHI series lenses, the backfocal adjustment is needed to adjust the focus for a different field of view.

C-mount is the most common optics mount in the industrial market. It is defined by a flange focal distance of 17.526 mm, a diameter of 1” (25.4 mm) with 32 threads per inch.

CS-mount is a less popular and 5 mm shorter version of the C-mount, with a flange focal distance of 12.526 mm. A CS-mount camera presents various issues when used together with C-mount optics, especially if the latter is designed to work at a precise back focal distance.
**F-mount** is a bayonet-style mount originally developed by Nikon for its 35 mm format cameras, and is still found in most of its digital SLR cameras. It is commonly used with bigger sensors, e.g. full-frame or line-scan cameras. Lenses can be easily swapped out thanks to the bayonet mount, but no back focal adjustment is possible.

**Mxx-mount** are different types of camera mounts defined by their diameter (e.g. M72, M42), thread pitch (e.g. 1 mm, 0.75 mm) and flange focal distance. They are a common alternative to the F-mount for larger sensors.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Diagonal</th>
<th>Width</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3&quot;</td>
<td>6.000</td>
<td>4.800</td>
<td>3.600</td>
</tr>
<tr>
<td>1/2.5&quot;</td>
<td>7.182</td>
<td>5.760</td>
<td>4.290</td>
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<tr>
<td>1&quot;</td>
<td>8.000</td>
<td>6.400</td>
<td>4.800</td>
</tr>
<tr>
<td>1/1.8&quot;</td>
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<tr>
<td>2/3&quot;</td>
<td>11.000</td>
<td>8.800</td>
<td>6.600</td>
</tr>
<tr>
<td>3&quot;</td>
<td>15.000</td>
<td>12.800</td>
<td>9.600</td>
</tr>
<tr>
<td>4/3&quot;</td>
<td>22.500</td>
<td>18.800</td>
<td>13.500</td>
</tr>
<tr>
<td>Full frame - 35 mm</td>
<td>43.300</td>
<td>36.000</td>
<td>24.000</td>
</tr>
</tbody>
</table>

Each camera mount is more commonly used with certain camera sensor formats. The most typical sensor formats are listed below. It is important to remember that these are not absolute values – i.e. two cameras listed with the same sensor format may differ substantially from one another in terms of aspect ratio (even if they have the same sensor diagonal). For example, the Sony Pregius IMX250 sensor is listed as 2/3" and has an active area of 8.45 mm x 7.07 mm. The CMOSIS CMV2000 sensor is also listed as 2/3" format but has an active area of 11.26 mm x 5.98 mm.
Focal Length

The focal length of an optical system is a measure of how strongly the system converges or diverges rays of light. For common optical systems, it is the distance over which collimated rays coming from infinity converge to a point. If collimated rays converge to a physical point, the lens is said to be positive (convex), whereas if rays diverge the focus point is virtual and the lens is said to be negative (concave cf. Fig. 9). All optics used in machine vision application are overall positive, i.e. they focus incoming light onto the sensor plane.

The magnification $M$ of an optics describes the ratio between image ($h'$) and object size ($h$):

$$M = \frac{h'}{h}$$

A useful relationship between working distance ($s$), magnification ($M$) and focal length ($f$) is the following:

$$s = \frac{f(M-1)}{M}$$

Macro and telecentric lenses are designed to work at a distance comparable to their focal length (finite conjugates), while fixed focal length lenses are designed to image objects located at a much greater distance than their focal length (infinite conjugates). It is thus convenient to classify the first group by their magnification, which makes it easier to choose the proper lens given the sensor and object size, and the latter by their focal length.

For fixed focal length lenses also follow the previous equation, it is possible to calculate the required focal length given the magnification and working distance, or the required working distance given the sensor size, field of view and focal length, etc. (some examples are given at the end of this section). For macro and telecentric lenses instead, the working distance and magnification are typically fixed.

Magnification and field of view

For optical systems used in machine vision, in which rays reflected from a faraway object are focused onto the sensor plane, the focal length can be also seen as a measure of how much area is imaged on the sensor (Field of View): the longer the focal length, the smaller the FoV and vice versa (this is not completely true for some particular optical systems, e.g. in astronomy and microscopy).

Back focal length adjustment

Many cameras are found not to respect the industrial standard for C-mount (17.52 mm), which defines the flange-to-detector distance (flange focal length). Besides all the issues involved with mechanical inaccuracy, many manufacturers don’t take into the due account the thickness of the detector’s protection glass which, no matter how thin, is still part of the actual flange to detector distance. This is why a spacer kit is supplied with Opto Engineering® telecentric lenses including instructions on how to tune the back focal length at the optimal value.
**F/# and depth of field**

Every optical system is characterized by an aperture stop, that determines the amount of light that passes through it. For a given aperture diameter $d$ and focal length $f$ we can calculate the optics F-number:

$$F/# = \frac{f}{d}$$

Typical F-numbers are F/1.0, F/1.4, F/2, F/2.8, F/4, F/5.6, F/8, F/11, F/16, F/22 etc. Every increment in the F-number (smaller aperture) reduces incoming light by a factor of 2.

The given definition of F-number applies to fixed focal length lenses where the object is located ‘at infinity’ (i.e. a distance much greater than its focal length). For macro and telecentric lenses where objects are at closer distance, instead the working F/# ($wF/#$) is used. This is defined as:

$$WF/# = (1 + M) \cdot F/#$$

A common F-number value is F/8, since smaller apertures could give rise to diffraction limitations, while lenses with larger apertures are more affected by optical aberrations and distortion.

The F-number affects the optics depth of field (DoF), that is the range between the nearest and farthest location where an object is acceptably in focus. Depth of field is quite a misleading concept, because physically there is one and only one plane in object space that is conjugate to the sensor plane. However, being mindful of diffraction, aberration and pixel size, we can define an “acceptable focusing distance” from the image conjugate plane, based on subjective criteria. For example, for a given lens, the acceptable focusing distance for a precision gauging application requiring a very sharp image is smaller than for a coarse visual inspection application.

A rough estimate of the field depth of telecentric and macro lenses (or fixed focal length lenses used in macro configuration) is given by the following formula:

$$DoF [mm] = WF/# \cdot p [\mu m] \cdot k / M^2$$

where $p$ is the sensor pixel size (in microns), $M$ is the lens magnification and $k$ is a dimensionless parameter that depends on the application (reasonable values are 0.008 for measurement applications and 0.015 for defect inspection). For example, taking $p = 5.5 \mu m$ and $k = 0.015$, a lens with 0.25X mag and WF/# = 8 has an approximate dof = 10.5 mm.
When designing a machine vision system, it is important to consider its performance limitations, in terms of optical parameters (FOV, DoF, resolution), aberrations, distortion and mechanical features.

Aberrations

"Aberrations" is a general category including the principal factors that cause an optical system to perform differently than the ideal case. There are a number of factors that do not allow a lens to achieve its theoretical performance.

Physical aberrations

The homogeneity of optical materials and surfaces is the first requirement to achieve optimum focusing of light rays and proper image formation. Obviously, homogeneity of real materials has an upper limit determined by various factors (e.g. material inclusions), some of which cannot be eliminated. Dust and dirt are external factors that certainly degrade a lens performance and should thus be avoided as much as possible.

Spherical aberration

Spherical lenses (Fig. 15) are very common because they are relatively easy to manufacture. However, the spherical shape is not ideal for perfect imaging - in fact, collimated rays entering the lens at different distances from the optical axis will converge to different points, causing an overall loss of focus. Like many optical aberrations, the blur effect increases towards the edge of the lens. To reduce the problem, aspherical lenses (Fig. 16) are often used - their surface profile is not a portion of a sphere or cylinder, but rather a more complex profile apt to minimize spherical aberrations. An alternative solution is working at high F/#'s, so that rays entering the lens far from the optical axis and causing spherical aberration cannot reach the sensor.

![Fig. 15: Lens with spherical aberration.](image1.png)

![Fig. 16: Aspherical lens.](image2.png)
The refractive index of a material is a number that describes the scattering angle of light passing through it—essentially how much rays are bent or refracted—and it is a function of the wavelength of light. As white light enters a lens, each wavelength takes a slightly different path. This phenomenon is called dispersion and produces the splitting of white light into its spectral components, causing chromatic aberration. The effect is minimal at the center of the optics, growing towards the edges.

Chromatic aberration causes color fringes to appear across the image, resulting in blurred edges that make it impossible to correctly image object features. While an achromatic doublet can be used to reduce this kind of aberration, a simple solution when no color information is needed is using monochrome light. Chromatic aberration can be of two types: longitudinal (Fig. 17) and lateral (Fig. 18), depending on the direction of incoming parallel rays.
**Astigmatism**

Astigmatism (Fig. 19) is an optical aberration that occurs when rays lying in two perpendicular planes on the optical axis have different foci. This causes blur in one direction that is absent in the other direction. If we focus the sensor for the sagittal plane, we see circles become ellipses in the tangential direction and vice versa.

![Fig. 19: Astigmatism aberration.](image)

**Coma**

Coma aberration (Fig. 20) occurs when parallel rays entering the lens at a certain angle are brought to focus at different positions, depending on their distance from the optical axis. A circle in the object plane will appear in the image as a comet-shaped element, which gives the name to this particular aberration effect.

![Fig. 20: Coma aberration.](image)
**Field curvature**

Field curvature aberration (Fig. 21) describes the fact that parallel rays reaching the lens from different directions do not focus on a plane, but rather on a curved surface. This causes radial defocusing, i.e. for a given sensor sensor position, only a circular crown will be in focus.

![Field curvature aberration](image)

**Distortion**

With a perfect lens, a squared element would only be transformed in size, without affecting its geometric properties. Conversely, a real lens always introduces some geometric distortion, mostly radially symmetric (as a reflection of the radial symmetry of the optics). This radial distortion can be of two kinds: barrel and pincushion distortion. With barrel distortion, image magnification decreases with the distance from the optical axis, giving the apparent effect of the image being wrapped around a sphere. With pincushion distortion image magnification increases with the distance from the optical axis. Lines that do not pass through the center of the image are bent inwards, like the edges of a pincushion.

![Barrel and pincushion distortion](image)

**What about distortion correction?**

Since telecentric lenses are a real world object, they show some residual distortion which can affect measurement accuracy. Distortion is calculated as the percent difference between the real and expected image height and can be approximated by a second order polynomial.

If we define the radial distances from the image center as follows

\[ Ra = \text{actual radius} \]
\[ Re = \text{expected radius} \]

the distortion is computed as a function of Ra:

\[ \text{dist} (Ra) = (Ra - Re)/Ra = c \cdot Ra^2 + b \cdot Ra + a \]

where a, b and c are constant values that define the distortion curve behavior; note that “a” is usually zero as the distortion is usually zero at the image center. In some cases, a third order polynomial could be required to get a perfect fit of the curve.

In addition to radial distortion, also trapezoidal distortion must be taken into account. This effect can be thought of as the perspective error due to the misalignment between optical and mechanical components, whose consequence is to transform parallel lines in object space into convergent (or divergent) lines in image space. Such effect, also known as “keystone” or “thin prism”, can be easily fixed by means of pretty common algorithms which compute the point where convergent bundles of lines cross each other.

An interesting aspect is that radial and trapezoidal distortion are two completely different physical phenomena, hence they can be mathematically corrected by means of two independent space transform functions which can also be applied subsequently.

An alternative (or additional) approach is to correct both distortions locally and at once: the image of a grid pattern is used to define the distortion error amount and its orientation zone by zone. The final result is a vector field where each vector associated to a specific image zone defines what correction has to be applied to the x,y coordinate measurements within the image range.
Why GREEN light is recommended for telecentric lenses?

All lenses operating in the visible range, including OE Telecentric lenses, are achromatized through the whole VIS spectrum. However, parameters related to the lens distortion and telecentricity are typically optimized for the wavelengths at the center of the VIS range, that is green light. Moreover, the resolution tends to be better in the green light range, where the achromatization is almost perfect.

"Green" is also better than "Red" because a shorter wavelength range increases the diffraction limit of the lens and the maximum achievable resolution.

Contrast, resolution and diffraction

Contrast

Defects and optical aberrations, together with diffraction, contribute to image quality degradation. An efficient way to assess image quality is to calculate contrast, that is the difference in luminance that makes an object - its representation in the image or on a display - distinguishable. Mathematically, contrast is defined as

\[ C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

where \( I_{\text{max}} \) (\( I_{\text{min}} \)) is the highest (lowest) luminance.

In a digital image, 'luminance' is a value that goes from 0 (black) to a maximum value depending on color depth (number of bits used to describe the brightness of each color). For typical 8-bit images (in grayscale, for the sake of simplicity), this value is \( 2^8 - 1 = 255 \), since this is the number of combinations (counting from the zero 'black' string) one can achieve with 8 bits sequences, assuming 0-1 values for each.

Lens resolving power: transfer function

The image quality of an optical system is usually expressed by its transfer function (TF). TF describes the ability of a lens to resolve features, correlating the spatial information in object space (usually expressed in line pair per millimeter) to the contrast achieved in the image.

What's the difference between MTF (Modulation Transfer Function) and CTF (Contrast Transfer Function)?

CTF expresses the lens contrast response when a "square pattern" (chessboard style) is imaged; this parameter is the most useful in order to assess edge sharpness for measurement applications. On the other hand, MTF is the contrast response achieved when imaging a sinusoidal pattern in which the grey levels range from 0 and 255; this value is more difficult to convert into any useful parameter for machine vision applications. The resolution of a lens is typically expressed by its MTF (modulation transfer function), which shows the response of the lens when a sinusoidal pattern is imaged.
Optics and sensor resolution

The cutoff spatial frequency is not an interesting parameter, since machine vision systems cannot reliably resolve features with very low contrast. It is thus convenient to choose a limit frequency corresponding to 20% contrast.

A commonly accepted criterion to describe optical resolution is the Rayleigh criterion, which is connected to the concept of resolution limit. When a wave encounters an obstacle - e.g. it passes through an aperture - diffraction occurs. Diffraction in optics is a physical consequence of the wave-like nature of light, resulting in interference effects that modify the intensity pattern of the incoming wavefront.

Since every lens is characterized by an aperture stop, the image quality will be affected by diffraction, depending on the lens aperture: a dot-like object will be correctly imaged on the sensor until its image reaches a limit size; anything smaller will appear to have the same image - a disk with a certain diameter depending on the lens F/# and on the light wavelength.

This circular area is called the Airy disk, having a radius of

\[ r_A = 1.22 \frac{\lambda f}{d} \]

where \( \lambda \) is the light wavelength, \( f \) is the lens focal length, \( d \) is the aperture diameter and \( f/d \) is the lens F-number. This also applies to distant objects that appear to be small.

If we consider two neighboring objects, their relative distance can be considered the “object” that is subject to diffraction when it is imaged by the lens. The idea is that the diffraction of both objects’ images increases to the point that it is no longer possible to see them as separate. As an example, we could calculate the theoretical distance at which human eyes cannot distinguish that a car’s lights are separated.

The Rayleigh's criterion states that two objects are not distinguishable when the peaks of their diffraction patterns are closer than the radius of the Airy Disk \( r_A \) (in image space).

The cutoff frequency is defined as the value \( w \) for which CTF is zero, and it can be estimated as

\[ w_{\text{cut-off}} = \frac{1}{(WF/\# \cdot \lambda (\text{mm}))} \]

For example, an Opto Engineering® TC23036 lens (WF/# F/8) operating in green light (\( \lambda = 0.000587 \text{ mm} \)) has a cut-off spatial frequency of about

\[ w_{\text{cut-off}} = \frac{8 \cdot 0.000587 \text{ mm}}{} = 210 \text{ lp/mm} \]

The Opco Engineering® TC12120 telecentric lens, for example, will not distinguish feature closer than

\[ r_A = 1.22 \cdot 0.587 \mu \text{m} \cdot 8 = 5.7 \mu \text{m} \]

in image space (e.g. on the sensor). The minimum resolvable size in image space is always 2 \( r_A \), regardless of the real world size of the object. Since the TC12120 lens has 0.052X magnification and 2\( r_A = 11.4 \mu \text{m} \), the minimum real-world size of the object that can be resolved is 11.4 \mu \text{m} / 0.052 = 220 \mu \text{m}.

For this reason, optics should be properly matched to the sensor and vice versa: in the previous example, there is no advantage to use a camera with 2 \mu \text{m} pixel size, since every “dot like” object will always cover more than one pixel. In this case, a higher resolution lens or a different sensor (with larger pixels) should be chosen.

The Transfer Function of the whole system should then be considered, assessing the contribution from both the optics and the sensor. It is important to remember that the actual resolution limit is not only given by the lens F/# and the wavelength, but also depends on the lens aberrations: hence, the real spatial frequency to be taken into account is the one described by the MTF curves of the desired lens.
Reflection, transmission and coatings

When light encounters a surface, a fraction of the beam is reflected, another fraction is refracted (transmitted) and the rest is absorbed by the material. In lens design, we must achieve the best transmission while minimizing reflection and absorption. While absorption is usually negligible, reflection can be a real problem: the beam is in fact not only reflected when entering the lens (air-glass boundary) but also when it exits the lens (glass-air). Let’s suppose that each surface reflects 3% of incoming light: in this case, a two lenses system has an overall loss of $3\times3\times3\% = 81\%$. Optical coatings – one or more thin layers of material deposited on the lens surface – are the typical solution: a few microns of material can dramatically improve image quality, lowering reflection and improving transmission.

**Transmission** depends considerably on the light wavelength: different kind of glasses and coatings helps to improve performance in particular spectral regions, e.g. UV or IR. Generally, good transmission in the UV region is more difficult to achieve.

![Fig. 27: Percent transmittance of different kind of glasses.](image)

**Anti-reflective (AR) coatings** are thin films applied to surfaces to reduce their reflectivity through optical interference. An AR coating typically consists of a carefully constructed stack of thin layers with different refractive indices. The internal reflections of these layers interfere with each other so that a wave peak and a wave trough come together and extinction occurs, leading to an overall reflectance that is lower than that of the bare substrate surface.

**Anti-reflection coatings** are included on most refractive optics and are used to maximize throughput and reduce ghosting. Perhaps the simplest, most common anti-reflective coating consists of a single layer of Magnesium Fluoride ($\text{MgF}_2$), which has a very low refractive index (approx. 1.38 at 550 nm).

**Hard carbon anti-reflective HCAR coating**: HCAR is an optical coating commonly applied to Silicon and Germanium designed to meet the needs of those applications where optical elements are exposed to harsh environments, such as military vehicles and outdoor thermal cameras.

This coating offers highly protective properties coupled with good anti-reflective performance, protecting the outer optical surfaces from high velocity airborne particles, seawater, engine fuel and oils, high humidity, improper handling, etc. It offers great resistance to abrasion, salts, acids, alkalis, and oil.
Vignetting

Light that is focused on the sensor can be reduced by a number of internal factors, that do not depend on external factors.

Mount vignetting occurs when light is physically blocked on its way to the sensor. Typically this happens when the lens image circle (cross section of the cone of light projected by the lens) is smaller than the sensor size, so that a number of pixels are not hit by light, thus appearing black in the image. This can be avoided by properly matching optics to sensors: for example, a typical 2/3” sensor (8.45 x 7.07 mm, 3.45 µm pixel size) with 11 mm diagonal would require a lens with a (minimum) image circle of 11 mm in diameter.

Aperture vignetting is connected to the optics F/#: a lens with a higher F/# (narrower aperture) will receive the same light from most directions, while a lens with a lower F/# will not receive the same amount of light from wide angles, since light will be partially blocked by the edges of the physical aperture.

Cos^4 vignetting describes the natural light falloff caused by light rays reaching the sensor at an angle.

The light falloff is described by the cos^4(θ) function, where θ is the angle of incoming light with respect to the optical axis in image space.

The drop in intensity is more significant at wide incidence angles, causing the image to appear brighter at the center and darker at the edges.

Fig. 28: Example of an image showing vignetting.

Fig. 29: Lens with low F/# (left) and high F/# (right) seen from the optical axis (top) and off-axis (button).

Fig. 30: Cos^4 vignetting. Light fall off caused by θ the angle with incoming light with respect to the optical axis.
Many different types of optics are available in the industry, each tailored for different uses and applications. Below is a brief overview of the most common lens types, along with their working principles and common applications.

**TELECENTRIC LENSES**

Telecentric lenses represent a special class of optics designed to only collect collimated light ray bundles (i.e. parallel to the optical axis, see Fig. 31), thus eliminating perspective errors.

Since only rays parallel to the optical axis are accepted, the magnification of a telecentric lens is independent of the object location. This unique feature makes telecentric lenses perfectly suited for measurement applications, where perspective errors and changes in magnification can lead to inconsistent measurements. Because of its design, the front element of a telecentric lens must be at least as large as the desired FOV, making these lenses inadequate to image very large objects.

The following drawings (Fig. 32) show the difference between common optics (entocentric) and telecentric lenses. Fixed focal length lenses are entocentric lenses, meaning that they collect rays diverging from the optical axis. This allows them to cover large FoVs but since magnification is different at different working distances, these lenses are not suited to determine the true dimensions of an object.

**Fig. 31**: Telecentric optics accepts only rays parallel to the optics axis.

**Fig. 32**: a) The design of a telecentric lens is such that objects at different distances from the lens appear to have the same size.

**Fig. 32**: b) With entocentric optics, a change in the working distance is seen on the sensor as perspective error.

**Benefits of bi-telecentric lenses**

*Better Magnification Constancy*

Standard telecentric lenses accept ray cones whose axis is parallel to the main optical axis; if the lens is only telecentric in object space, ray cones passing through the optical system reach the detector from different angles depending upon the field position. Moreover the optical wavefront is completely asymmetric since incoming telecentric rays become non-telecentric in image space. As a consequence, the spots generated by ray cones on the detector plane change in shape and dimension from point to point in image space (the point-spread function becomes non-symmetrical and a small circular spot grows larger and turns elliptical as you move from the image center towards the borders).

Even worse, when the object is displaced, rays coming from a certain field point generate a spot that moves back and forth over the image plane, thus causing a significant change in magnification. For this reason non bi-telecentric lenses show a lower magnification constancy although their telecentricity might be very good if measured only in the object space.
Bi-telecentric lenses are telecentric in both object and image space, which means that principal rays are parallel not only when entering but also when exiting the lens. This feature is essential to overcome all the accuracy issues concerned with mono-telecentric lenses such as point spread function inhomogeneity and lack of magnification constancy through the field depth.

**Increased field depth**

Field depth is the maximum acceptable displacement of an object from its best focus position. Beyond this limit the image resolution becomes poor, because the rays coming from the object can’t create sufficiently small spots on the detector: blurring effect occurs because geometrical information carried by the optical rays spread over too many image pixels.

Depth of field basically depends upon the optics F/#, which is inversely proportional to the lens aperture diameter: the higher the f-number the larger the field depth, with a quasi-linear dependence.

Increasing the F/# reduces ray cones divergence, allowing for smaller spots to form onto the detector; however raising the F/# over certain values introduces diffraction effects which limit the maximum achievable resolution.

Bi-telecentricity is beneficial in maintaining a very good image contrast even when looking at very thick objects (see Fig. 34): the symmetry of the optical system and the rays parallelism help the image spots with staying symmetrical, which reduces the blur effect. This results in a field depth being perceived as 20-30% larger compared to non bi-telecentric optics.

**Even detector illumination**

Bi-telecentric lenses boast a very even illumination of the detector, which comes useful in several applications such as LCD, textile and print quality control (Fig. 35).

When dichroic filters have to be integrated in the optical path for photometric or radiometric measurements, bi-telecentricity assures that the ray fan axis strikes the filter normal to its surface, thus preserving the optical band-pass over the whole detector area.

Fig. 33: (a) In a non image space telecentric lens (left) ray cones strike the detector at different angles.

Fig. 33: (b) In a bi-telecentric lens (right) ray cones are parallel and reach the image sensor in a way independent on the field position.

Fig. 34: Image of a thick object viewed throughout its entire depth by a bi-telecentric lens.

Fig. 35: A bi-telecentric lens is interfaced with a tunable filter in order to perform high resolution colour measurements. The image-side telecentricity ensures that the optical bandpass is homogeneous over the entire filter surface and delivers an even illumination of the detector, provided the object is evenly illuminated too.
How to choose the right telecentric lens

Having fixed working distance and aperture, telecentric lenses are classified by their magnification and image circle. Choosing the right telecentric lens is easy: we must find the magnification under which the image fit the sensor.

**Example.** We need to measure the geometrical feature of a mechanical part (nut) using a telecentric lens and a 2048 x 2048, 5.5 µm sensor. The nut is inscribed in a 10 mm diameter circle with 2 mm uncertainty on the sample position. What is the best choice?

Given the camera resolution and pixel size (2048 x 2048 pix, 5.5 µm), the sensor dimensions are calculated to be 11.26 x 11.26 mm. The FOV must contain a 12 mm diameter circle, hence the minimum magnification required is 0.938X.

The Opto Engineering® TC23009 telecentric lens (M=1.000X, image circle 11 mm) would give a FOV of 11.26 mm x 11.26 mm, but because of mechanical vignetting the actual FOV is only a 11 mm diameter circle. In this case, if a more accurate part placement cannot be guaranteed, a lens with lower mag or a larger image circle must be chosen.

Using the Opto Engineering® TC2MHR016-9 lens (M=0.767X, image circle 16.0 mm) we find a FOV of 14.68 x 14.68 mm which is a very close match.

**UV TELECENTRIC OPTICS**

Since the diffraction limit allows higher resolution at shorter wavelengths (see Fig. 36), UV optics can reach superior results compared to standard lenses and can efficiently operate with pixels as small as 1.75 µm.

For example, the Opto Engineering® TCUV series telecentric lenses operate in the near UV range and deliver extremely high resolution for very demanding measurement applications.

![UV Telecentric Lens](image)

**Fig. 36:** The graph shows the limit performances (diffraction limit) of two lenses operating at working F/# 8. The standard lens operates at 587 nm (green light) while the UV lens operates at 365 nm.
Why Opto Engineering® telecentric lenses don’t integrate an iris?

Our TC lenses don’t feature an iris, but we can easily adjust the aperture upon request prior to shipping the lens, without any additional costs or delays for the customer.

The reasons why our lenses don’t feature an iris are so many that the proper question would be “why other manufacturers integrate irises?”:

- adding an iris makes a lens more expensive because of a feature that would only be used once or twice throughout the product life
- iris insertion makes the mechanics less precise and the optical alignment much worse
- we would be unable to test the lenses at the same aperture that the customer would be using
- iris position is much less precise than a metal sheet aperture: this strongly affects telecentricity
- the iris geometry is polygonal, not circular: this changes the inclination of the main rays across the FOV, thus affecting the lens distortion and resolution
- irises cannot be as well centered as fixed, round, diaphragms: proper centering is essential to ensure a good telecentricity of the lens
- only a circular, fixed, aperture makes brightness the same for all lenses
- an adjustable iris is typically not flat and this causes uncertainty in the stop position, which is crucial when using telecentric lenses!
- iris is a moving part that can be dangerous in most industrial environments. Vibrations could easily disassemble the mechanics or change the lens aperture
- the iris setting can be accidentally changed by the user and that would change the original system configuration
- end users prefer having less options and only a few things that have to be tuned in a MV system
- apertures smaller than what is delivered by OE as a standard will not make sense as the resolution will decay because of diffraction limit; on the other hand, much wider apertures would cause a reduction of the field depth.

The standard aperture of OE lenses is meant to optimize image resolution and field depth.

Why OE Télécentric lenses don’t feature a focusing mechanism?

As with the iris, a focusing mechanism would generate a mechanical play in the moving part of the lens, thus making it worse the centering of the optical system and also causing trapezoidal distortion. Another issue is concerned with radial distortion: the distortion of a telecentric lens can be kept small only when the distances between optical components are set at certain values; displacing any element from the correct position would increase the lens distortion. A focusing mechanism makes the positioning of the lenses inside the optical system uncertain and the distortion value unknown; the distortion would then be different from the values obtained in our quality control process.
Many machine vision applications require a complete view of an object surface since many features to be inspected are located on the object sides rather than on top.

Most cylindrical objects such as bottles and containers, as well as many kinds of mechanical parts require an inspection of the side surfaces to detect scratches and impurities or to read barcodes or, again, to ensure that a label has been printed correctly.

In these cases, the most common approach is to use multiple cameras (usually 3 or 4) in order to achieve several side views of the part, in addition to the top view. This solution, besides increasing the cost of the system, often creates a bottleneck in the system performances, since the electronics or software must process different images from different cameras simultaneously.

In other cases, vision engineers prefer to scan the outer surface with line scan camera systems.

This approach also shows many technical and cost disadvantages: the object must be mechanically rotated in the FOV which also affects the inspection speed; moreover, line-scan cameras require very powerful illumination. Also, the large size of linear detectors increases the optical magnification of the system, thus reducing field depth.

The 360° optics category encompasses different optical solutions that capture rays diverging from the object (see Fig. 37), thus imaging not only the object surface in front of the lens, but also the object’s lateral surface (see optical diagram below). The following images illustrate the working principle applied to a pericentric lens (PC), a catadioptric lens (PCCD), a pinhole lens (PCHI) and a boroscope lens (PCPB). Other 360° optical solutions combine telecentric optics and mirror arrays, allowing you to get a complete view of a sample with just one camera (TCCAGE, PCPW and PCMP series).
MACRO LENSES

Macro lenses are fixed focal length lenses whose working distance is comparable to their focal length. The recommended working distance from the object is usually fixed, hence macro optics are usually described by their magnification.

Since macro lenses are specifically designed to image small and fixed FoVs, they tend to have extremely low geometrical distortion. For example, the distortion of Opto Engineering® MC series lenses range from <0.05% to <0.01%.
FIXED FOCAL LENGTH LENSES

Fixed focal length lenses are entocentric lenses, meaning that they collect rays diverging from the optical axis (see Fig. 45). Fixed focal length lenses are commonly used optics in machine vision, being affordable products that are well suited for standard applications. Knowing the basic parameters - focal length and sensor size - it is easy to calculate the field of view and working distance; the focus can be adjusted from a minimum working distance to infinity; usually also the iris is controlled mechanically, allowing you to manually adjust the lens F/# and consequently the light intensity, field depth and resolution.

Example. A ceramic tile (100 x 80 mm) must be inspected with a fixed focal length lens from 200 mm away. Which lens would you choose? The Camera sensor has 2592 x 1944 res, with 2.2 µm pixels.

Recalling basic lens equations:

\[ \frac{1}{s'} + \frac{1}{s} = \frac{1}{f} \]

\[ M = \frac{h'}{h} = \frac{s'}{s} \]

we find:

\[ \frac{1}{s} ( \frac{h}{h'} - 1 ) = \frac{1}{f} \]

thus

\[ WD = -s = -f ( \frac{h}{h'} - 1 ) \]

or consequently:

\[ f = \frac{s}{ ( \frac{h}{h'} - 1 ) } \]

and also

\[ h = h' ( 1 + \frac{s}{f} ) \]

keeping in mind that s and h’ (object position with respect to the lens and image height) are customarily negative, while f and h (focal length and object height) are customarily positive. Also, in machine vision, we take h as the maximum value for the desired field of view and h’ as the short side of the sensor, to make sure the minimum requested field of view is covered.

Given the sensor resolution and pixel size, we can calculate the sensor dimensions. We set h’ = -4.28 mm and h = 100 mm. Hence, setting s = -200 mm we find f = 8.2 mm. With a standard 8 mm lens we would cover a slightly wider FOV (137 x 102 mm).

Extension tubes

For most standard lenses the working distance (WD) is not a fixed parameter. The focusing distance can be changed by adjusting a specific knob. Nevertheless, there is always a minimum object distance (MOD) below which focusing becomes impossible. Adding an extension tube (see Fig. 46) between the lens and the camera increases the back focal length, making it possible to reduce the MOD. This also increases the magnification of the lens or, in other words, reduces the FOV. While very common in the vision industry, this procedure should be avoided as much as possible, because it degrades the lens performance (resolution, distortion, aberrations, brightness, etc.). In these cases, it is recommended to use lenses natively designed to work at short working distances (macro lenses).

Fig. 45: Entocentric optics accept rays diverging from the lens.

Fig. 46: Extension tubes for fixed focal length lenses.
VARIFOCAL LENSES

Varifocal lenses are lenses with variable focal length, which can be adjusted by moving groups of optical elements with respect to each other inside the lens. The variable focal length allows for multiple combinations of working distances and magnifications, offering several different configurations with a single lens. Varifocal lenses, though, have the same reliability issues of fixed focal length lenses, plus more uncertainty caused by the relative motion of lens groups inside the assembly.

ZOOM LENSES

Zoom lenses (parfocal lenses) are a special type of varifocal optics in which the working distance is kept constant when changing focal length (i.e. focus is maintained throughout the process). Actually, a zoom lens is generally defined as a lens that can change magnification without changing its working distance: in this category, we can also find macro zoom (e.g. Opto Engineering® MCZR and MZMT) and telecentric zoom lenses (Opto Engineering® TCZR).

SCHEIMPFLUG OPTICS

Scheimpflug optics are a special class of lenses, either of the fixed focal, macro or telecentric type, designed to meet the Scheimpflug criterion.

Suppose that the object plane of an optical setup is not parallel to the image plane (e.g. a camera-lens system imaging a flat target at 45°): this causes the image to be sharp only where the focus plane and the target plane intersect.

Since the image and object planes are conjugated, tilting the first plane by a certain angle will also cause the latter to tilt by a corresponding angle. Once the focus plane is aligned to the target plane, focus across the image is restored.

The angle at which the sensor plane must be tilted is given by the Scheimpflug criterion:

\[ \tan(\theta') = M \cdot \tan(\theta) \]

\[ \theta' = \arctan(M \cdot \tan(\theta)) \]

where \( M \) is the lens magnification, \( \theta' \) is the image plane tilt angle (i.e. on the sensor side) and \( \theta \) is the object plane tilt angle.

It is clear that at high magnifications this condition is impossible to meet, since an object plane tilted by 45° would require to tilt the sensor by 80°, causing severe mechanical and vignetting issues (cf. Fig. 47, where \( M=5 \) black, \( M=1 \) blue, \( M=0.25 \) red).

Image plane tilting is practically realized by changing the angle of the camera with respect to the optics by means of special tiltable mounts: the picture below illustrates an example of a Scheimpflug telecentric setup.
All objects with an absolute temperature over 0 K emit infrared (IR) radiation. Infrared radiant energy is determined by the temperature and emissivity of an object and is characterized by wavelengths ranging from 0.76 µm (the red edge of the visible range) to 1000 µm (beginning of microwaves range). The higher the temperature of an object, the higher the spectral radiant energy, or emittance, at all wavelengths and the shorter the peak wavelength of the emissions. Due to limitations on detector range, IR radiation is often divided into three smaller bands based on the response of various detectors.

SWIR (0.9-1.7 µm) is also called the «reflected infrared» region since radiation coming from a light source is reflected by the object in a similar manner as in the visible range. SWIR imaging requires some sort of illumination in order to image an object and can be performed only if some light, such as ambient moon light or stars light is present. In fact the SWIR region is suitable for outdoor, night-time imaging. SWIR imaging lenses are specifically designed, optimized, and anti-reflection coated for SWIR wavelengths. Indium Gallium Arsenide (InGaAs) sensors are the primary sensors used in SWIR, covering typical SWIR band, but can extend as low as 0.550 µm to as high as 2.5 µm.

A large number of applications that are difficult or impossible to perform using visible light are possible using SWIR InGaAs based cameras: nondestructive identification of materials, their composition, coatings and other characteristics, Electronic Board Inspection, Solar cell inspection, Identifying and Sorting, Surveillance, Anti-Counterfeiting, Process Quality Control, etc...

MWIR (3-5 µm) and LWIR (8-14 µm) regions are also referred to as “thermal infrared” because radiation is emitted from the object itself and no external light source is needed to image the object. Two major factors determine how bright an object appears to a thermal imager: the object’s temperature and its emissivity (a physical property of materials that describes how efficiently it radiates). As an object gets hotter, it radiates more energy and appears brighter to a thermal imaging system. Atmospheric obscurants cause much less scattering in the MWIR and LWIR bands than in the SWIR band, so cameras sensitive to these longer wavelengths are highly tolerant of smoke, dust and fog.

• MWIR collects the light in the 3 µm to 5 µm spectral band. MWIR cameras are employed when the primary goal is to obtain high-quality images rather than focusing on temperature measurements and mobility. The MWIR band of the spectrum is the region where the thermal contrast is higher due to blackbody physics; while in the LWIR band there is quite more radiation emitted from terrestrial objects compared to the MWIR band, the amount of radiation varies less with temperature: this is why MWIR images generally provide better contrast than LWIR. For example, the emissive peak of hot engines and exhaust gasses occurs in the MWIR band, so these cameras are especially sensitive to vehicles and aircraft. The main detector materials in the MWIR are InSb (Indium antimonide) and HgCdTe (mercury cadmium telluride) also referred to as MCT and partially lead selenide (PbSe).

• LWIR collects the light in the 8 µm to 14 µm spectral band and is the wavelength range with the most available thermal imaging cameras. In fact, according to Planck’s law, terrestrial targets emit mainly in the LWIR. LWIR systems applications include thermography/temperature control, predictive maintenance, gas leak detection, imaging of scenes which span a very wide temperature range (and require a broad dynamic range), imaging through thick smoke, etc... The two most commonly used materials for uncooled detectors in the LWIR are amorphous silicon (a-Si) and vanadium oxide (VOx), while cooled detectors in this region are mainly HgCdTe.

Athermalization. Any material is characterized by a certain temperature expansion coefficient and responds to temperature variations by either increasing or decreasing its physical dimensions. Thus, thermal expansion of optical elements might alter a system’s optical performance causing defocusing due to a change of temperature. An optical system is athermalized if its critical performance parameters (such as Modulation Transfer Function, Back Focal Length, Effective Focal Length, …) do not change appreciably over the operating temperature range.

Athermalization techniques can be either active or passive. Active athermalization involves motors or other active systems to mechanically adjust the lens elements’ position, while passive athermalization makes use of design techniques aimed at compensating for thermal defocusing, by combining suitably chosen lens materials and optical powers (optical compensation) or by using expansion rods with very different thermal expansion coefficients that mechanically displace a lens element so that the system stays in focus (mechanical compensation).
Illumination is one of the most critical components of a machine vision system. The selection of the appropriate lighting component for a specific application is very important to ensure that a machine vision system performs its tasks consistently and reliably.

The main reason is that improper illumination results in loss of information which, in most cases, cannot be recovered via software. This is why the selection of quality lighting components is of primary importance: there is no software algorithm capable of revealing features that are not correctly illuminated.

To make the most appropriate choice, one must consider many different parameters, including:

- Lighting geometry
- Light source type
- Wavelength
- Surface property of the material to be inspected or measured (e.g. color, reflectivity)
- Item shape
- Item speed (inline or offline application)
- Mechanical constraints
- Environment considerations
- Cost

Since many parameters must be considered, the choice can be difficult and sometimes the wisest advice is to perform feasibility studies with different light types to reveal the features of interest. On the other hand, there are a number of simple rules and good practices that can help select the proper lights and improve the image quality.

For every application, the main objectives are the following:

1. Maximizing the contrast of the features that must be inspected or measured
2. Minimizing the contrast of the features of no interest
3. Getting rid of unwanted variations caused by:
   a. Ambient light
   b. Differences between items that are non-relevant to the inspection task
Light in machine vision

In machine vision, light is mostly characterized by its wavelength, which is generally expressed in nm (nanometers).

Basically light is electromagnetic radiation within a certain portion of the electromagnetic spectrum (cf. Fig. 1): it can be quasi-monochromatic (which means that it is characterized by a narrow wavelength band, i.e. with a single color) or white (distributed across the visible spectrum, i.e. it contains all colors).

Light visible to the human eye has wavelengths in the range of 400-700 nm, between the infrared (with longer wavelengths) and the ultraviolet (with shorter wavelengths): special applications might require IR or UV light instead of visible light.

Fig. 1: Electromagnetic spectrum.
LED illumination

There are many different types of light sources available (Fig. 3) including the following:

- Incandescent lamps
- Fluorescent lamps
- LED lights

LED lights are by far the most commonly used in machine vision because they offer a number of advantages, including:
- Fast response
- Suitable for pulse and strobe operations
- Mechanical resistance
- Longer lifetime, higher output stability
- Ease of creating various lighting geometry

Incandescent lamps are the well-known glass bulbs filled with low pressure, inert gas (usually argon) in which a thin metal wire (tungsten) is heated to high temperatures by passing an electric current through it. The glowing metal emits light on a broad spectrum that goes from 400 nm up to the IR. The result is a white, warm light (corresponding to a temperature of 2870 K) with a significant amount of heat being generated.

Fluorescent lamps are vacuum tubes in which UV light is first produced (by interaction between mercury vapor and highly energetic electrons produced by a cathode) and then is adsorbed by the tube walls, coated with fluorescent and phosphorescent material. The walls then re-emit light over a spectrum that again covers the whole visible range, providing a “colder” white light source.

LEDs (Light Emitting Diodes) produce light via the annihilation of an electron-hole pair in a positive/negative junction of a semiconductor chip. The light produced by an LED depends on the materials used in the chip and is characterized by a narrow spectrum, i.e. it is quasi-monochromatic. White light is produced as in the fluorescent lamps, but the blue light is absorbed and re-emitted in a broad spectrum slightly peaked in the blue region.
LED power supply and output

An LED illuminator can be controlled by either setting the voltage V across the circuit or by directly feeding the circuit with electric current I.

One important consideration is that the luminous flux produced by a single LED increases almost linearly with the current while it does not do so with respect to the voltage applied: 1% uncertainty on the driving current will translate into 1% luminance uncertainty, while 1% uncertainty on the input voltage can result in a several percentage points variation (Fig. 4).

For this reason, it is suggested to directly regulate the current and not the voltage, so that the light output is stable, tightly controlled and highly repeatable.

For example, in measurement applications, it is paramount to obtain images with a stable grey level background to ensure consistency of the results: this is achieved by avoiding light flickering and ensuring that the LED forward current of the telecentric light is precisely controlled: this is why Opto Engineering® LTLCHP telecentric illuminators feature built-in electronics designed to have less than 1‰ variation in LED forward current intensity leading to very stable performances.

LED pulsing and strobing

LEDs can be easily driven in a pulsed (on/off) regime and can be switched on and off in sequence, turning them on only when necessary. Usage of LEDs in pulsed mode has many advantages including the extension of their lifespan.

If the LED driving current (or voltage) is set to the nominal value declared by the LED manufacturer for continuous mode, we talk about pulsed mode: the LED is simply switched on and off. LEDs can also be driven at higher intensities (i.e. overdriven) than the nominal values, thus producing more light but only for a limited amount of time: in this case we say that the LED is operated in strobed mode.

Strobing is needed whenever the application requires an increased amount of light to freeze the motion of fast moving objects, in order to eliminate the influence of ambient light, to preserve the LED lifetime and to synchronize the ON time of your light (ton) with the camera and item to be inspected.

To properly strobe an LED light, a few parameters must be considered (Fig. 5 and 6):

- **Max pulse width or ON time (t_{on max})**: the maximum amount of time for which the LED light can be switched on at the maximum forward current.
- **Duty cycle D** is defined as (usually expressed in %):

  \[ D = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} \]

  Where \( t_{on} \) is the amount of time for which the LED light is off and \( T = t_{on} + t_{off} \) is the cycle period. The duty cycle gives the fraction in % of the cycle time during which the LEDs can be switched on. The period \( T \) can also be given as the cycle frequency \( f = \frac{1}{T} \), expressed in Hertz (Hz).
LED lifetime

The life of an LED is defined as the time that it takes for the LED luminance to decrease to 50% of its initial luminance at an ambient temperature of 25°C.

Line speed, strobing and exposure time

When dealing with online applications, there are some important parameters that have to be considered. Specifically, depending on the object speed and image sharpness that is required for the application, the camera exposure time must be always set to the minimum in order to freeze motion and avoid image blurring. Additionally, black and opaque objects that tend to absorb instead of reflecting light, are particularly critical.

As an example, let’s suppose to inspect an object moving with speed $v_i$ using a lens with magnification $m$ and a camera with pixel size $p_i$. The speed of the object on the sensor will be $m$ times $v_i$:

$$v_i = m \cdot v_i$$

Therefore the space travelled by the object $x_i$ during the exposure time $t$ is $x_i = v_i t$. If this space is greater than the pixel size, the object will appear blurred over a certain number of pixels. Suppose that we can accept a 3 pixels blur: in other words, we require that

$$x_i = v_i t = m \cdot v_i t < 3 p_i$$

so that the camera exposure time $t$ is required to be

$$t < \frac{3 p_i}{m \cdot v_i}$$

For example, using $p_i = 5.5 \, \mu m$, $m = 0.66$, $v_i = 300 \, \text{mm/s}$ (i.e. a line speed of 10,800 samples/hr on a 100 mm FoV) we find a maximum exposure time of $t = 83 \, \mu s$.

At such speed, the amount of light emitted by LED illuminator used in continuous mode is hardly ever enough - so that strobing the illuminator for an equivalent amount of time is the best solution.

Another parameter that we can adjust in order to get more light into the system is the lens F/#: by lowering the lens F/# we will gather more light; however, this will lower the depth of field of the system. Moreover, this might also lower the image quality since, in general, a lens performs better in the center and worse towards the edges due to lens aberrations, leading to an overall loss of sharpness. Increasing the camera gain is another way, however this always introduces a certain amount of noise, thus again leading to a degraded image where fewer details can be distinguished.

As a result, it is always a good practice to choose sufficiently bright lighting components, allowing you to correctly reveal the features of interest the inspected of object when used in combination with lenses set at the optimum F/# and without the need to digitally increase the camera gain.
Illumination geometries and techniques

How to determine the best illumination for a specific machine vision task?

There are in fact several aspects that must be taken into account to help you choose the right illumination for your vision system with a certain degree of confidence.

Application purpose

This is by far the first point that must be clear.

If we want to inspect the surface of an object to look for defects or features such as printed text, then front illumination is needed - i.e. light coming from the camera side. Selecting the proper light direction or angle of incidence on the target surface as well as other optical properties such as diffuse or direct light depends on the specific surface features that must be highlighted.

If, on the other side, we plan to measure the diameter or the length of an object or we want to locate a through-hole, the best choice to maximize contrast at the edges is back illumination - i.e. light is blocked by the object on its way to the camera. The choice is not so obvious when dealing with more complex situations such as transparent materials and sometimes mixed solutions must be taken into account.

Illumination angle

Once we have established whether front or back illumination is more suitable, we must set the angle at which light hits the object surface. Although the angle may vary, there are two important subgroups of front and backlight illumination: bright field and dark field illumination. The four combinations that follow are described below (Fig. 7).

![Diagram of illumination geometries and techniques](image-url)
In bright field, front light illumination, light reflected by a flat surface is collected by the optics.

This is the most common situation, in which non-flat features (e.g., defects, scratches etc.) can scatter light outside the maximum acceptance angle of the lens, showing dark characteristics on a bright background (the bright field - see Fig. 8 and 10.a 10.b).

Bright field, front light can be produced by LED barlights or ringlights, depending on the system symmetry (Fig. 9).

In both cases LED light can be direct or diffused by a medium (sometimes the latter is to prefer to avoid uneven illumination on reflective surfaces).

In dark field, front light illumination, reflected light is not collected by the optics. In this way, only scattered light is captured, enhancing the non-planar features of the surface as brighter characteristics on a dark background (the dark field - see Fig. 11 and 13.a - 13.b).

Again, this effect is commonly reproduced by means of low angle ringlights (Fig. 12).
In bright field, backlight illumination, light is either stopped or transmitted by the surface if the material is opaque (Fig. 14) or transparent.

In the first case, we see the outline of the object (black object on white background - see Fig. 16 and 18).

In the latter, the non-planar features of the transparent object show up dark on a white background; in this second case, contrast is usually low unless the transparent surfaces present sharp curvatures (e.g. air bubble inclusions in plastic).

These lighting techniques can be achieved using diffuse backlights (Fig. 15a, 15b and 16) or telecentric illuminators, specifically designed for high accuracy applications (Fig. 17 and 18).
In dark field, backlight illumination, only light transmitted by the sample and scattered by non-flat features will be collected, enhancing such features as bright on the dark background (Fig. 19).

This can be obtained by means of ringlights or bar lights positioned behind a transparent sample.

**Coaxial illumination.** When front light hits the object surface perpendicular to the object plane, we speak of coaxial illumination.

Coaxial illumination can additionally be collimated, i.e. rays are parallel to the optical axis (within a certain degree). To obtain this illumination set up, coaxial boxes are available for use in combination with any type of lens (either fixed focal, macro or telecentric) or telecentric lenses with built-in coaxial illumination can be used (such as Opto Engineering® TCCX series).

The difference lies in the degree of collimation which results in the amount of contrast that is possible to achieve searching for defects on highly reflective surfaces. See Fig. 21 and 22.

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*Fig. 19: Dark field back light illumination scheme.*

*Fig. 20: Coaxial illumination scheme (non collimated).*

*Fig. 21: Coaxial illumination geometry (standard and collimated).*

*Fig. 22: Image of engraved sample with coaxial illumination.*
**Combined and advanced illumination solutions.** Sometimes in order to inspect very complex object geometries it is necessary to combine different types of lights to effectively reveal surface defects.

For example, the combination of a dome and a low angle light is very effective in providing uniform illumination over the entire field of view.

An example of "combined" lighting is the Opto Engineering® LTDMHLA series, featuring all-in-one dome and low angle ring lights which can be operated simultaneously or independently of each other (see Fig. 25).

In fact, dome lights are sometimes also referred to as "cloudy day" illuminators because they provide uniform light as on a cloudy day.

Another type of lighting geometry is tunnel illumination: these lights are designed to provide uniform illumination on long and thin cylindrical objects and they feature a circular aperture on top (as dome lights).
Telecentric illumination

Telecentric illumination is needed in a wide variety of applications including:

- High speed inspection and sorting: in fact, when coupled with a telecentric lens, the high throughput allows for extremely short exposure times
- Silhouette imaging for accurate edge detection and defect analysis
- Measurement of reflective cylindrical objects: diffuse backlights can generate undesired reflections from the edges of shiny round objects, making them look smaller than they are and leading to inaccurate measurements. Since collimated rays are typically much less reflected, telecentric illuminators can effectively eliminate this “border effect” ensuring accurate and consistent readings (see Fig. 26)
- Any precision measurement application where accuracy, repeatability and high throughput are key factors

The use of a collimated light in combination with a telecentric lens increases the natural depth of field of the telecentric lens itself by approximately +20/30% (this however also depends on other factors such as the lens type, light wavelength and pixel size).

Additionally, thanks to the excellent light coupling, the distance between the object and the light source can be increased where needed without affecting image quality. This happens because the illuminator’s numerical aperture (NA) is lower than the telecentric lens NA.

Therefore, the optical system behaves as if the lens had the same NA as the illuminator in terms of field depth, while maintaining the same image resolution given by the actual telecentric lens NA.

Collimated light is the best choice if you need to inspect objects with curved edges; for this reason, this illumination technique is widely used in measurement systems for shafts, tubes, screws, springs, o-rings and similar samples.
Wavelength and optical performance

Many machine vision applications require a very specific light wavelength that can be generated with quasi-monochromatic light sources or with the aid of optical filters.

In the field of image processing, the choice of the proper light wavelength is key to emphasize only certain colored features of the object being imaged.

The relationship between wavelength (i.e. the light color) and the object color is shown in Fig. 27. Using a wavelength that matches the color of the feature of interest will highlight this specific feature and vice versa, i.e. using opposite colors to darken non-relevant features (see Fig. 28).

For example, green light makes green features appear brighter on the image sensor while red light makes green features appear darker on the sensor. On the other hand, white light will contrast all colors, however this solution might be a compromise.

Additionally, it must be considered that there is a big difference in terms of sensitivity between the human eye and a CMOS or CCD sensor. Therefore, it is important to do an initial assessment of the vision system to determine how it perceives the object, in fact what human eyes see might be misleading.

Monochromatic light can be obtained in two ways: we can prevent extraneous wavelengths from reaching the sensor by means of optical filters, or we can use monochromatic sources.

**Optical filters** allow only certain wavelengths of light to be transmitted. They can be used either to allow light of a specified wavelength to pass through (band-pass filters) or to block desired wavelengths (e.g., low-pass filters for UV light only).

Color filters can block other non-monochromatic light sources often present in industrial environments (e.g., sunlight, ceiling lights etc.), however they also limit the amount of light that actually reaches the sensor.

On the other hand, **quasi-monochromatic sources** only produce light of a certain wavelength within a usually small bandwidth. Either way, if we select monochromatic (e.g., green) light, every non-green feature will appear dark grey or black on the sensor, depending on the filter bandwidth and the color of the feature. This gives us a simple way to enhance contrast by using monochromatic light with respect to the use of white light (Fig. 29 - 34).

Additionally, in some cases a specific wavelength might be preferred for other reasons: for example, Opto Engineering® telecentric lenses are usually optimized to work in the visible range and they offer the best performance in terms of telecentricity and distortion when used with green light. Furthermore, green light is a good tradeoff between the resolution limit (which improves with shorter wavelengths) and the transmission characteristics of common glasses (which in fact have low transmission at short wavelengths).

In cases where any wavelength will fit the application, one might choose a specific LED color just based on cost considerations.
Polarizing filters consist of special materials characterized by a distinctive optical direction: all light oscillating in this direction passes through, while the other components of the wave are suppressed. Since light reflected by a surface is polarized in the direction parallel to the surface itself, such reflection can be significantly reduced or blocked by means of two polarization filters - one on the light and one on the lens. Polarizing filters are used to eliminate glare effects occurring when imaging reflective materials, such as glass, plastic etc.
Structured illumination

The projection of a light pattern on a surface can easily give information on its 3D dimensional features (Fig. 35). For example, if we observe a line projected from the vertical direction with a camera looking from a known angle, we can determine the height of the object where the line is projected. This concept can be extended using various different patterns, such as grids, crosses, dots etc.

Although both LED and laser sources are commonly used for pattern projection, the latter present several disadvantages (Fig. 36). The laser light profile of the line has a Gaussian shape, being higher at the center and decreasing at the edges of the stripe. Additionally, projecting a laser onto a surface produces the so-called “speckle effect”, i.e. an interference phenomenon that causes loss of edge sharpness of the laser line, due to the high coherent nature of the laser light.

With laser emitters the illumination decays both across the line cross section and along the line width. Additionally, lines from laser emitters show blurred edges and diffraction/speckle effects.

On the other hand, using LED light for structured illumination will eliminate these issues. Opto Engineering® LED pattern projectors feature thinner lines, sharper edges and more homogeneous illumination than lasers. Since light is produced by a finite-size source, it can be stopped by a physical pattern with the desired features, collected by a common lens and projected on the surface.

Light intensity is constant through the projected pattern with no visible speckle, since LED light is much less coherent than laser light. Additionally, white light can be easily produced and used in the projection process.

Illumination safety and class risks of LEDs according to EN62471

EC/EN 62471 gives guidance for evaluating the photobiological safety of lamps including incoherent broadband sources of optical radiation such as LEDs (but excluding lasers) in the wavelength range from 200 nm through 3000 nm.

According to EN 62471 light sources are classified into risk groups according to their potential photobiological hazard.

<table>
<thead>
<tr>
<th>Risk Group</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exempt</td>
<td>No photobiological hazard</td>
</tr>
<tr>
<td>Group Ia</td>
<td>No photobiological hazard under normal behavioral limitations</td>
</tr>
<tr>
<td>Group II</td>
<td>Does not pose hazard due to aversion response to bright light or thermal discomfort</td>
</tr>
<tr>
<td>Group III</td>
<td>Hazardous even for momentary exposure</td>
</tr>
</tbody>
</table>
A camera is a remote sensing device that can capture and store or transmit images. Light is collected and focused through an optical system on a sensitive surface (sensor) that converts intensity and frequency of the electromagnetic radiation to information, through chemical or electronic processes.

The simplest system of this kind consists of a dark room or box in which light enters only from a small hole and is focused on the opposite wall, where it can be seen by the eye or captured on a light sensitive material (i.e. photographic film). This imaging method, which dates back centuries, is called ‘camera obscura’ (Latin for ‘dark room’), and gave the name to modern cameras.

Camera technology has hugely improved in the last decades, since the development of Charge Coupled Device (CCD) and, more recently, of CMOS technology. Previous standard systems, such as vacuum tube cameras, have been discontinued.

The improvements in image resolution and acquisition speed obviously also improved the quality and speed of machine vision cameras.
Camera types

Matrix and Line scan cameras

Cameras used in machine vision applications can be divided in two groups: area scan cameras (also called matrix cameras) and line scan cameras. The first are simpler and less technically demanding, while the latter are preferred in some situations where matrix cameras are not suitable. Area scan cameras capture 2-D images using a certain number of active elements (pixels), while line scan cameras sensors are characterized by a single array of pixels.

Sensor sizes and resolution

Sensor sizes (or formats) are usually designated with an imperial fraction value – i.e. 1/2", 2/3". However, the actual dimensions of a sensor are different from the fraction value, which often causes confusion among users. This practice dates back to the 50’s at the time of TV camera tubes and is still the standard these days. Also, it is always wise to check the sensor specifications, since even two sensors with the same format may have slightly different dimensions and aspect ratios. Spatial resolution is the number of active elements (pixels) contained in the sensor area: the higher the resolution, the smaller the detail we can detect on the image.

Suppose we need to inspect a 30 x 40 mm FoV, looking for 40 x 40 µm defects that must be viewed on at least three pixels.

There can be \(30\times40/(0.04\times0.04) = 0.75\times10^6\) defects. Assuming a minimum of 3 pixels are required to see a defect, we need a camera with at least 2.25 MP pixels. This gives the minimum resolution required for the sensor, although the whole system resolution (also including the lens resolution) must always be assessed. Table 1 gives a brief overview of some common sensor dimensions and resolutions. It is important to underline that sensors can have the same dimensions but different resolution, since the pixel size can vary. Although for a given sensor format smaller pixels lead to higher resolution, smaller pixels are not always ideal since they are less sensitive to light and generate higher noise; also, the lens resolution and pixel size must always be properly matched to ensure optimal system performances.

Table 1: Examples of common sensor sizes and resolutions.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>1/3&quot;</th>
<th>1/2&quot;</th>
<th>2/3&quot;</th>
<th>1&quot;</th>
<th>4/3&quot;</th>
<th>4 K (linear)</th>
<th>8 K (linear)</th>
<th>12 K (linear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor size (mm)</td>
<td>4.80 x 3.60</td>
<td>6.40 x 4.80</td>
<td>8.45 x 7.07</td>
<td>12.8 x 9.64</td>
<td>18.1 x 13.6</td>
<td>28.7</td>
<td>41</td>
<td>64</td>
</tr>
<tr>
<td>Pixel size (μm)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>5.3</td>
</tr>
<tr>
<td>Resolution (mm)</td>
<td>960 x 720</td>
<td>1280 x 960</td>
<td>1690 x 1414</td>
<td>2560 x 1928</td>
<td>3620 x 2720</td>
<td>4000</td>
<td>8000</td>
<td>12000</td>
</tr>
<tr>
<td>Resolution (Pixel)</td>
<td>0.6 M</td>
<td>1.2 M</td>
<td>2.5 M</td>
<td>5 M</td>
<td>10 M</td>
<td>4 K</td>
<td>8 K</td>
<td>12 K</td>
</tr>
</tbody>
</table>

Sensor types: CCD and CMOS

The most popular sensor technologies for digital cameras are CCD and CMOS.

**CCD (charged-couple device)** sensors consist of a complex electronic board in which photosensitive semiconductor elements convert photons (light) into electrons. The charge accumulated is proportional to the exposure time.

Light is collected in a potential well and is then released and read out in different ways (cf. Fig. 3). All architectures basically shift the information to a register, sometimes passing through a passive area for storage.

The charge is then amplified to a voltage signal that can be read and quantified.

**Table 1:** Examples of common sensor sizes and resolutions.
CMOS (complementary metal-oxide semiconductor) sensors are conceptually different from CCD sensors, since the readout can be done pixel by pixel rather than in sequential mode. In fact, signal is amplified at each pixel position, allowing you to achieve much higher frame rates and to define custom regions of interest (ROIs) for the readout.

CMOS and CCD sensors were invented around the same time and, although historically CCD technology was regarded as superior, in recent years CMOS sensors have caught up in terms of performance.

Global and rolling shutter (CMOS). In rolling shutter CMOS sensors, the acquisition is progressive from the upper to the last row of pixels, with up to 1/frame rate time difference between the first and the last row. Once the readout is complete, the progressive acquisition process can start again. If the object is moving, the time difference between pixels is clearly visible on the image, resulting in distorted objects (see Fig. 4). Global shutter is the acquisition method in which all pixels are activated simultaneously, thus avoiding this issue.

Sensor and camera features

Sensor characteristics

Pixel defects can be of three kinds: hot, warm and dead pixels. Hot pixels are elements that always saturate (give maximum signal, e.g. full white) whichever the light intensity is. Dead pixels behave the opposite, always giving zero (black) signal. Warm pixels produce random signal. These kinds of defects are independent of the intensity and exposure time, so they can be easily removed – e.g. by digitally substituting them with the average value of the surrounding pixels.

Noise. There are several types of noise that can affect the actual pixel readout. They can be caused by either geometric, physical and electronic factors, and they can be randomly distributed as well as constant. Some of them are presented below:

- Shot noise is a consequence of the discrete nature of light. When light intensity is very low - as it is considering the small surface of a single pixel - the relative fluctuation of the number of photons in time will be significant, in the same way as the heads or tails probability is significantly far from 50% when tossing a coin just a few times. This fluctuation is the shot noise.
- Dark current noise is caused by the electrons that can be randomly produced by thermal effect. The number of thermal electrons, as well as the related noise, grows with temperature and exposure time.
- Quantization noise is related to the conversion of the continuous value of the original (analog) voltage value to the discrete value of the processed (digital) voltage.
- Gain noise is caused by the difference in behavior of different pixels (in terms of sensitivity and gain). This is an example of ‘constant noise’ that can be measured and eliminated.

Sensitivity is a parameter that quantifies how the sensor responds to light. Sensitivity is strictly connected to quantum efficiency, that is the fraction of photons effectively converted into electrons.

Dynamic range is the ratio between the maximum and minimum signal that is acquired by the sensor. At the upper limit, pixels appear to be white for every higher value of intensity (saturation), while pixels appear black at the lower limit and below.

The dynamic range is usually expressed by the logarithm of the min-max ratio, either in base-10 (decibel) or base-2 (doublings or stops), as shown in Table 2. Human eyes, for example, can distinguish objects both under starlight and on a bright sunny day, corresponding to a 90 dB difference in intensity. This range, though, cannot be used simultaneously, since the eye needs time to adjust to different light conditions.

A good quality LCD has a dynamic range of around 1000:1, and some of the latest CMOS sensors have measured dynamic ranges of about 23 000:1 (reported as 14.5 stops).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Decibels</th>
<th>Stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3.01</td>
<td>1</td>
</tr>
<tr>
<td>3.16</td>
<td>5</td>
<td>1.66</td>
</tr>
<tr>
<td>4</td>
<td>6.02</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>3.32</td>
</tr>
<tr>
<td>32</td>
<td>15.1</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>6.64</td>
</tr>
<tr>
<td>1024</td>
<td>30.1</td>
<td>10</td>
</tr>
<tr>
<td>10 000</td>
<td>50</td>
<td>13.3</td>
</tr>
<tr>
<td>1 000 000</td>
<td>60</td>
<td>19.9</td>
</tr>
<tr>
<td>1 073 741 824</td>
<td>90.3</td>
<td>30</td>
</tr>
<tr>
<td>10 000 000 000</td>
<td>100</td>
<td>33.2</td>
</tr>
</tbody>
</table>

Table 2: Dynamic range $D$, Decibels ($10 \log D$) and Stops ($\log_2 D$).
Sensitivity, linearity and noise

Dark current

Sensor non-uniformity and defect pixel

Spectral sensitivity

Measuring procedure

Test measuring amount of light at increasing exposure time, from closed shutter to saturation. Quantity of light is measured (e.g. photometer).

Measured from dark images taken at increasing exposure times. Since dark current is temperature dependent, behavior at different T can be given.

A number of images are taken without light (to see hot pixels) and at 50% saturation. Parameters of spatial distortion are calculated using Fourier algorithms.

Images taken at different wavelengths.

Result

Quantum efficiency (photons converted over total incoming photons ratio in %)

Temporal dark noise, in electrons (e-)

Absolute sensitivity threshold (minimum number of photons to generate a signal)

Dynamic range, in stops

SNR, in stops

Saturation capacity (maximum number of electrons at saturation)

Signal registered in absence of light, in electrons per second

Dark and bright signal non-uniformity

Dark and bright spectrograms and (logarithmic) histograms

Spectral sensitivity curve

Camera Parameters

Exposure time is the amount of time in which light is allowed to reach the sensor. The higher this value, the higher the quantity of light represented on the resulting image.

Increasing the exposure time is the first and easiest solution when light is not enough but it is not free from issues: first, noise always increases with the exposure time; also, blur effects can appear when dealing with moving objects. In fact, if the exposure time is too high, the object will be impressed on a number of different pixels, causing the well-known ‘motion blur’ effect (see Fig. 5).

On the opposite side, too long exposure times can lead to overexposure – namely, when a number of pixels reach maximum capacity and thus appear to be white, even if the light intensity on each pixel is actually different.
Camera Link is a standard for high-speed transmission of digital video. AIA standard defines cable, connector and camera functionality between camera and frame grabber.

**Speed.** Camera Link offers very high performance in terms of speed. It usually has different bandwidth configurations available, e.g. 255 MB/s, 510 MB/s and 680 MB/s. The bandwidth determines the ratio between image resolution and frame rate: a typical basic-configuration camera can acquire 1 Mpixel image at 50 frames/s or more; a full-configuration camera can acquire 4 Mpixel at more than 100 frames/s. Camera Link HS is the newer standard that can reach 300 MB/s on a single line, and up to 6 GB/s on 20 lines.

**Costs.** Camera Link offers medium- to high-performance acquisition, thus usually requiring more expensive cameras. Also, this standard requires a frame grabber in order to manage the hefty data load, not needed with other standards.

**Cables.** Camera Link standard defines a maximum length of 10 m for the cables; one cable is needed for basic configuration, where two are needed for full configuration cameras.

**Power over cable.** Camera Link offers a PoCL module (Power over Camera Link) that provides power to the camera. Also, several grabbers work with this feature.

**CPU usage.** Since Camera Link uses frame grabbers, which transfer images to a computer as stand-alone modules, this standard does not consume a lot of the system CPU.
CoaXPress

CoaXPress is the second standard, developed after Camera Link. It basically consists in power, data and control for the device sent through a coaxial cable.

**Speed.** A single cable can transmit up to 781.25 MB/s from the device to the frame grabber and 20 Mbit/s of control data from the frame grabber to the remote device, that is 5-6 times the GigE bandwidth. Some models can run also at half speed (390.625 MB/s). At present, up to 4 cables can be connected in parallel to the frame grabber, reaching a maximum bandwidth of approx. 1800 MB/s.

**Costs.** In the simplest case, CoaXPress uses a single coaxial line to transmit data, and coaxial cables are a simple and low-cost solution. On the other hand, a frame grabber is needed, i.e. an additional card must be installed, resulting in an additional cost on the system.

**Cables.** Maximum cable length is 40 m at full bandwidth, or 100 m at half bandwidth.

**Power over cable.** Voltage supply provided goes up to 13 W at 24 V, that is enough for many cameras.

**CPU usage.** CoaXPress, just like Camera Link, uses frame grabbers, which transfer images to computer as stand-alone modules, i.e. this standard is very light on consuming the system CPU.

GiG-E

GiG-E Vision is a camera bus technology that standardizes the Gigabit Ethernet, adding a ‘plug and play’ behavior (such as device discovery) to the latter. For its relatively high bandwidth, long cable length and diffused usage it is a good solution for industrial applications.

**Speed.** Gigabit Ethernet has a theoretical maximum bandwidth of 125 MB/s, that goes down to 100 MB/s when considering practical limitations. This bandwidth is comparable to FireWire standard and is second only to Camera Link.

**Costs.** System cost of GiG-E vision is moderate; cabling is cheap and it doesn’t require a frame grabber.

**Cables.** Cabling length is the keystone of GiG-E standard, going up to 100 m. This is the only digital solution comparable to analog visioning in terms of cable length, and this feature has helped GiG-E Vision to replace analog e.g. in monitoring applications.

**Power over cable.** Power over Ethernet (PoE) is often available on GiG-E cameras. Nevertheless, some Ethernet cards cannot supply enough power, so that powered switch, hub, or a PoE injector must be used.

**CPU usage.** CPU loads of a GiG-E system can be different depending on drivers used. Filtered drivers are more generic and easier to create and use, but operate on data packets at high level, affecting the system CPU. Optimized drivers are specifically written for a dedicated network interface card, that working at lower lever affects poorly the system CPU load.

USB 3.0

The USB (Universal Serial Bus) 3.0 standard is the second revision of USB standard, developed for computer communication. Building on USB 2.0 standard, it provides a higher bandwidth and up to 4.5 W of power.

**Speed.** While USB 2.0 goes up to 60 MB/s, USB 3.0 speed can reach 400 MB/s, similar to the Camera Link standard used in medium configuration.

**Costs.** USB cameras are usually low cost; also, no frame grabber is required. For this reason, USB is the cheaper camera bus in the market.

**Cables.** Passive USB 3.0 cable has a maximum length of about 7 meters, and active USB 3.0 cable can reach up to 50 m with repeaters.

**Power over cable.** USB 3.0 offers power up to 4.5 W that allows to get rid of a separate power cable.

**CPU usage.** USB 3.0 Vision permits image transfer directly into PC memory, without CPU usage.

GenICam Standard

The GenICam standard (GENeric Interface for CAMeras) is meant to provide a generic software interface for all cameras, independently from cameras hardware. Some of the new technology standard, anyway, are based on GenICam (es. Camera Link HS, CoaXPress, USB3 Vision).

GenICam standard purpose is to provide a ‘plug and play’ feature for every image system. In consists in three modules that help solving main tasks in machine vision filed in a generic way:

- **GenApi:** using a description file (XML), camera configuration and access-control is possible
- **Standard Feature Naming Convention (SFNC):** these are recommended names for common features in cameras to reach the goal of interoperability
- **GenTL:** describes the transport layer interface for enumerating cameras, grabbing images and transporting them to the user interface
Machine Vision is the discipline that encompasses imaging technologies and methods to perform automatic inspection and analysis in various applications, such as verification, measurement, process control. A very common approach in machine vision is to provide turnkey vision solutions, i.e. complete systems that can be rapidly and easily configured for use in the field. A vision system is usually made up of every component needed to perform the intended task, such as optics, lighting, cameras and software. When designing and building a vision system, it is important to find the right balance between performance and cost to achieve the best result for the desired application.

Usually vision systems are designed to work in on-line applications, where they have an immediate impact on the manufacturing process (real-time systems). A classic example of this on-line concept is the possibility to instantly reject a product deemed non-compliant: the way this decision is made, as well as the object features being evaluated, defines different classes of vision systems.
Applications

Vision systems can do many different things: measurement, identification, sorting, code reading, character recognition, robot guidance etc. They can easily interact with other machinery through different communication standards. Here below are some of the main application categories for a vision system:

**Measurement.** One of the most important uses of vision technology is to measure, at various degrees of accuracy, the critical dimensions of an object within predetermined tolerances. Optics, lighting and cameras must be coupled to effective software tools, since only robust subpixeling algorithms will allow to reach the accuracy often required in measurement applications (e.g. even down to 1 um).

**Defect detection.** Here various types of product defects have to be detected for cosmetic and/or safety reasons. Examples of cosmetic flaws are stains, spots, color clumps, scratches, tone variations, etc. while other surface and/or structural defects, such as cracks, dents, but also print errors etc. can have more severe consequences.

**Verification.** The third major aim of a vision system is checking that a product has been correctly manufactured, in a more general sense that goes beyond what previously described; i.e. checking the presence/absence of pills in a blister pack, the correct placement of a seal or the integrity of a printed label.
Types of vision systems

Several types of vision systems are available on the market, each being characterized by a different level of flexibility, performance and cost. Vision systems can usually be divided into three classes: PC based, compact and smart camera based.

**PC based.** The classic machine vision system consists of an industrial computer that manages and communicates with all the peripheral devices, such as cameras and lighting, quickly analyzing the information via software. This solution provides high computing power and flexibility, but size and cost can be significant. PC based systems are recommended for very complex applications, where multiple inspection tasks must be carried out at a fast rate with high-performance hardware.

**Compact.** A “lighter” version of a PC based system is called a Compact vision system. Although it may require some tradeoff between performance and cost, it is often enough for less demanding applications. Compact vision systems usually include a graphics card that acquires and transfers the information to a separate peripheral (e.g. an industrial tablet or an external monitor). Sometimes, compact vision systems not only manage the first level input - lightning, camera and trigger inputs - but also have embedded first level inputs.

**Smart Cameras based.** The simplest and most affordable vision systems are based on smart or intelligent cameras, normally used in combination with standard optics (typically a fixed focal length lens) and lighting. Although typically recommended for simpler applications, they are very easy to set up and provide similar functionalities to classic vision systems in a very compact form factor.

How a vision system works

The architecture of a vision system is strongly related to the application it is meant to solve. Some systems are “stand-alone” machines designed to solve specific problems (e.g. measurement/identification), while others are integrated into a more complex framework that can include e.g. mechanical actuators, sensors etc. Nevertheless, all vision systems operate by characterized by these fundamental operations:

**Image acquisition.** The first and most important task of a vision system is to acquire an image, usually by means of light-sensitive sensor. This image can be a traditional 2-D image, or a 3-D points set, or an image sequence. A number of parameters can be configured in this phase, such as image triggering, camera exposure time, lens aperture, lighting geometry, and so on.

**Feature extraction.** In this phase, specific characteristics can be extrapolated from the image: lines, edges, angles, regions of interest (ROIs), as well as more complex features, such as motion tracking, shapes and textures.

**Detection/segmentation.** At this point of the process, the system must decide which information previously collected will be passed on up the chain for further elaboration.

**High-level processing.** The input at this point usually consists of a narrow set of data. The purpose of this last step can be to:
- Classify objects or object’s feature in a particular class
- Verify that the input has the specifications required by the model or class
- Measure/estimate/calculate specific parameters as position or dimensions of object or object’s features