Optics: An Introduction

It is easy to overlook the contribution that optics make to a system; beyond basic lens parameters such as focal distance, the details can seem confusing. This Tech Tip presents a basic guide to optics to help users to make an informed choice and get the best performance out of their existing systems.

Lens

In simple terms, a lens is a device which refracts light, usually with the aim of bringing it to a focus. The first records of lenses involves them being used as a 'burning glass' to start fires. Modern lenses may be made of glass or plastics (poly-carbonate) and for vision stems they are generally specified in one of two ways: focal distance or magnification. Lens calculators are an easy way to find the focal distance of lens required for an application.

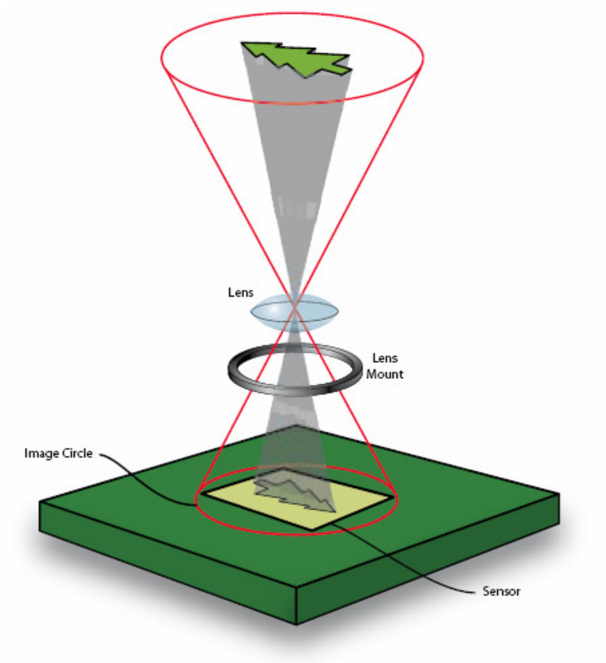

Figure 1 – Diagram showing object, lens and image onto the camera's sensor.

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Lens Specification

If the object to be viewed is significantly larger than the sensor size, then lens power is usually described in terms of focal length (for example 25mm). This is a measure of the strength of a lens – it is the distance behind the lens that parallel light is focussed. Practically this means that a shorter focal length lens gives a wider angle of view.

If the object is comparable to or smaller than the sensor size, macro lenses (consider them as microscope lenses) are used. These are defined by their magnification (for example 2x). So a 2x macro lens can view a filed of view half the size of the sensor. So a nominally ½" sensor that measures 6.4 x 4.8mm would see a field of view of 3.2 x 2.4mm.

The lens needs to be appropriate for the camera – so obviously it needs the correct lens mount (C-mount, CS-mount, F-mount et cetera) but also the lens must be able to project light onto the whole area of the sensor. As lenses generally have circular symmetry, this is called the image circle of the lens. If it is too small, the outer edges of the sensor will be shaded, resulting in vignetting, see Figure 2. Generally the effect is far less marked than this, resulting in some shading (darkening) towards the corners.

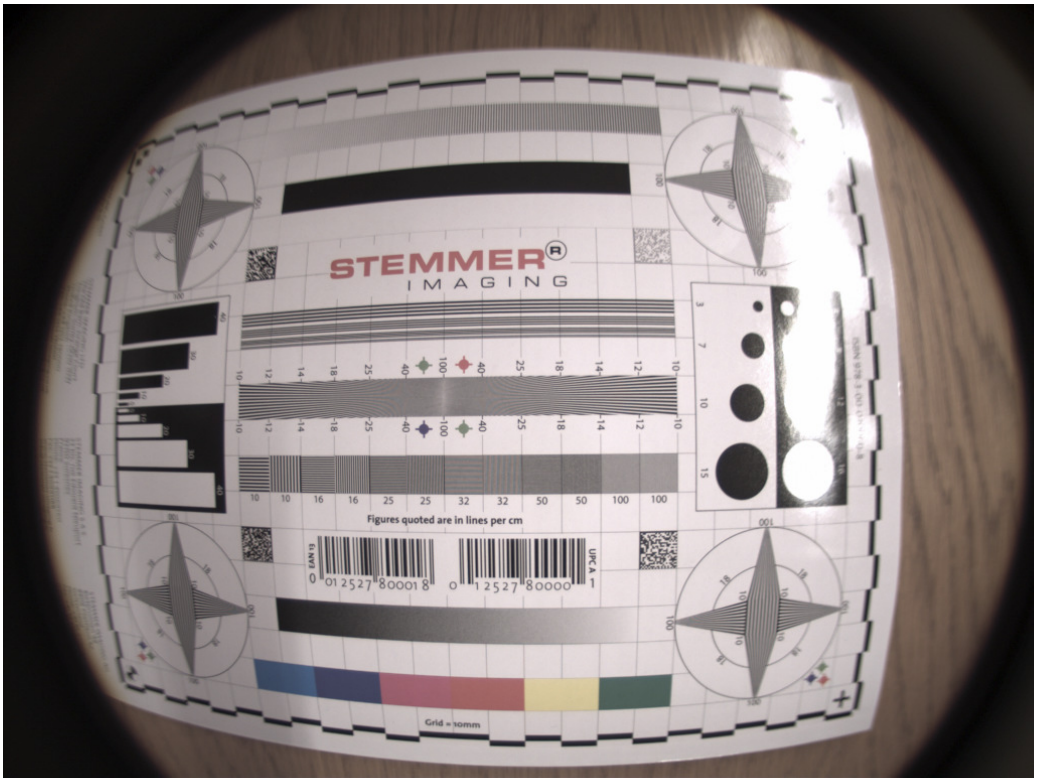

Figure 2 – An example of a lens with an image circle that is too small for the camera's sensor

Aperture

Most lenses have an aperture adjustment; this is the iris of the lens that is used to restrict the amount of light getting through to the sensor. It is described as an 'F-number' – this is a measure of the amount of light that can pass through the lens given by this formula:

$$F\_number = \frac{focal\_length}{aperture\_diameter}$$

This has the effect of making the F-number independent of the focal length of the camera. A lens's stated F-number is usually the maximum aperture the lens can manage, for example F1:1.4. This is usually related to the physical size (diameter) of the lens. A smaller F-number allows more light to pass through (also known as a 'fast' lens as it allows faster shutter speeds). For c-mount lenses F1:1.4 is fairly typical and F1:0.95 would be a fast lens. Aperture adjustment on a lens is normally marked with the following standard increments (f-stops):

- 1, 1.4,2,2.8,4,5.6,8,11,16

where each increasing f-stop allows half the amount of light through the lens.

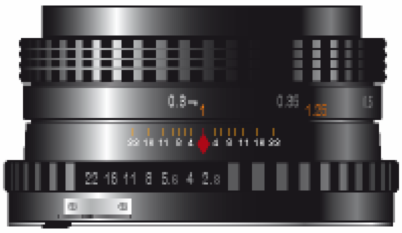

Figure 3 – F-mount lens diagram showing focus adjustment (top ring) and aperture adjustment (bottom ring) with f-stops marked.

Depth of Field

When a lens is focussed on a particular distance from the camera there is a small range around this distance which is also in focus (for example the distance ± 10%). This is known as the depth of field and is directly related to the aperture setting of the lens. With a wide open aperture (small f-stop) the light that comes to a focus on the sensor comes from a wide range of angles, see Figure 4a. However if the aperture is reduced ('stopped down'), only light from a narrow range of angles, around the optical axis, can get to the sensor. As well as reducing the amount of light that hits the sensor this also means that it is possible for an object to move toward or away from the camera to a greater extent before it 'goes out of focus', see Figure 4b. In different situations it may be desirable to have a small or a large depth of field.

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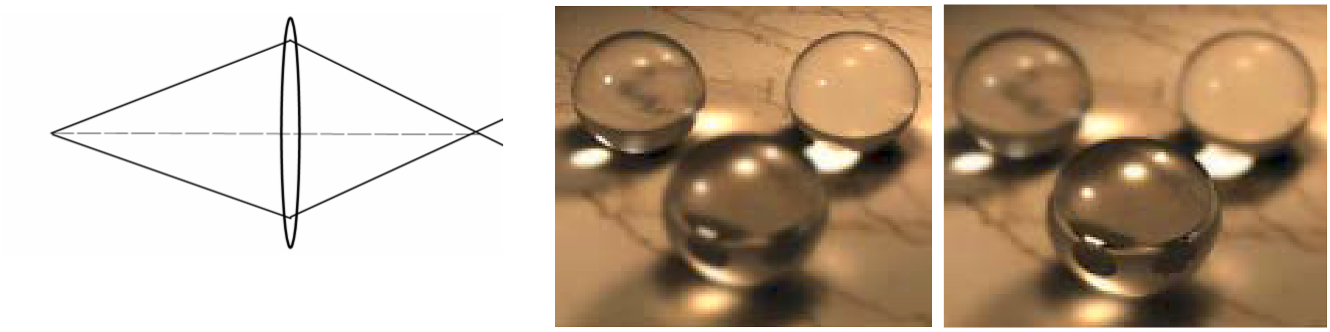
a)



b)

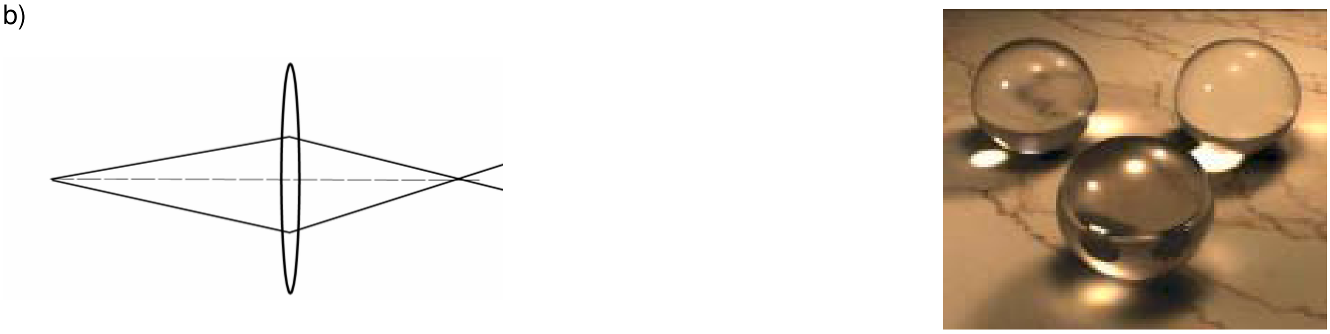


Figure 4 – a) (top) with a wide aperture more light enters the lens, from a wide range of angles. This gives a narrow depth of field as the light rays diverge rapidly from the focus point. Note that the marble images have either the foreground or the background in focus, not both. b) (bottom) a small aperture restricts the angles from which light can enter the lens to those close to the optical axis. This means that light rays diverge slowly from the point of focus, giving a large depth of focus – both the foreground and background are in focus.

Working Distance

Macro lenses often have no focus ring and a fixed working distance; however other lenses usually do have variable working distances. The minimum working distance at which the lens can focus (minimum operating distance or MOD) is usually limited by the mechanical movement of the lens. Extension tubes can be used to reduce the minimum operating distance, see Figure 5.

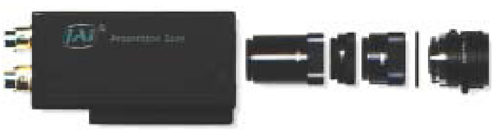


Figure 5 – Extension tubes are placed between the camera and the lens to reduce the minimum operating distance of the lens.

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However, there are downsides to the use of extension tubes:

- The lens will no longer focus to infinity – the *maximum* operating distance is reduced
- A decrease in the amount of light transmitted – this is effectively a reduction in aperture
- The depth of focus is reduced, sometimes dramatically
- A possible reduction in image quality as this amplifies irregularities in the lens glass.

Figure 6 shows a comparison of the use of macro lenses with the use of 'normal' lenses and extension. The macro lens has a fixed working distance of 140mm. To give the same field of view with the same camera, a 25mm lens with 20mm of extension needs a working distance of 8mm. This might place serious restrictions on the illumination that can be used. Also the macro lens (right0hand image in Figure 6) shows far more contrast, suggesting that the reduction in image quality with extension has seriously compromised the 25mm lens.

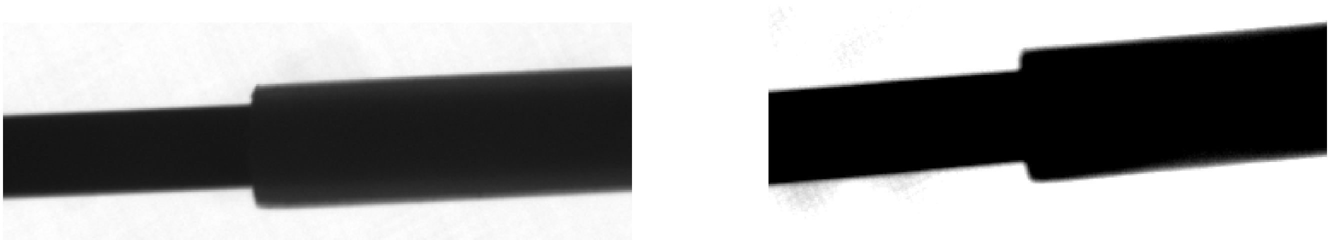

Figure 6 – A comparison of the use of a 25mm lens with 20mm extension (left) and a 3x macro lens (right)

Lens Imperfections

A lens is a physical device that doesn't always conform perfectly to the theory. White light is composed of a range of wavelengths, which refract to differing degrees. In a simple lens this produces 'chromatic aberration', a similar effect to shining white light through a prism. This brings red light to a focus at a different point to blue light, giving the blurring effect in monochrome images and coloured fringes in colour images, see Figure 7. This effect can be reduced by using monochromatic light.

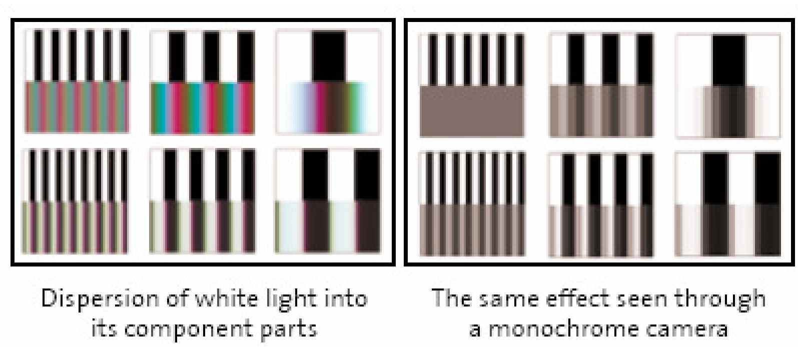

Figure 7 – Images showing chromatic aberration.

It is far easier (and therefore cheaper) to create lenses that have spherical surfaces, whereas theory suggests that 'aspherical' lens surfaces can give better performance, see Figure 8. Notice how the aspherical lens surfaces do a better job of bringing the light rays to a single point of focus.

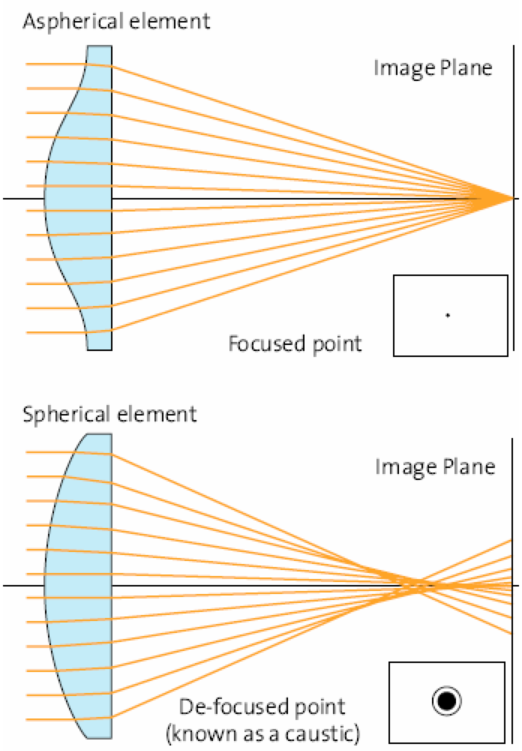

Figure 8 – Spherical vs aspherical lenses.

Lens Quality

The quality of an optical system (or 'resolving power') is its ability to resolve fine detail. A lens acts as a low-pass (smoothing) filter meaning that the finest detail is lost as it passes through the lens, even at the best focus. Resolving power (also known as the Modulation Transfer Function or MTF) is measured in line-pairs per mm. Figure 9 shows the effect. At the top of the image is a test pattern of high contrast black and white bars (a black and white bar make up a 'line pair'). After passing through the lens the finer detail is both blurred at the edges and reduced in contrast. The closer the line-pairs, the more noticeable the effect until eventually there is no contrast between the black and white bars. This is the same effect shown in Figure 6 with extension tubes. In real applications this might manifest itself as a few pixels of blur at what should be a sharp edge. Lens manufacturers typically discuss 'standard resolution' and 'megapixel' lenses, but higher quality optics will give more details. For example , the Linos MeVis-C range of lenses state that they resolve up to 200 line pairs per mm and are suitable for sensors with 12 megapixels.

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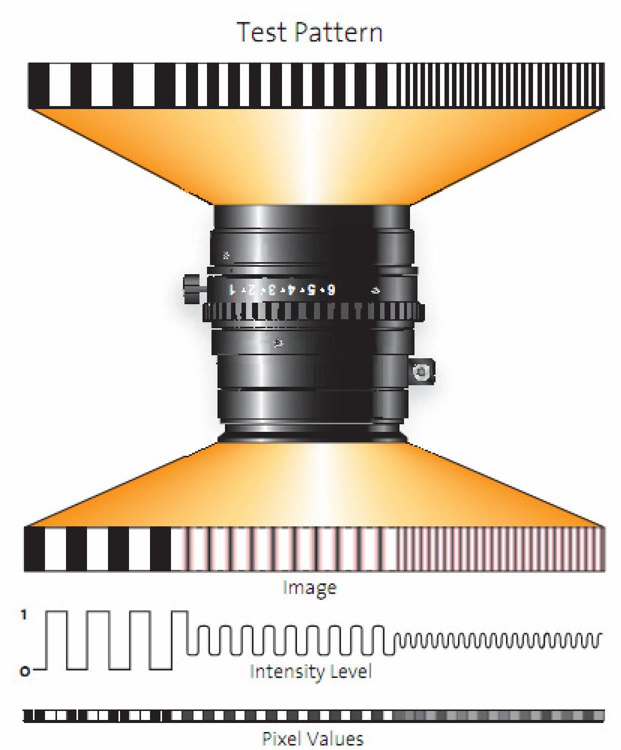

Figure 9 – Diagram showing the effect of lens resolving power on contrast and fine detail.

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