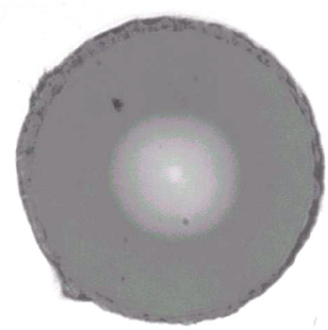
High quality imaging using a CCD camera

An image of the near-field light distribution in a multimode optical fibre was required so that the modal parameters could be determined. A high quality machine-vision CCD camera was chosen having 768 x 574 picture elements, or pixels. An imaging system was then designed to give (a) a field-of-view commensurate with the fibre sizes to be measured, and (b) an optical resolution commensurate with the physical pixel size in the camera.



Increasing the numerical aperture of the optics in this type of application does not always lead to a better image quality, if the pixel size is not sufficiently small to make use of the extra resolution

The optical resolution of an imaging system is determined by (a) diffraction limitations, and (b) aberrations. While it is normally desirable to optimise both of these attributes in an optical system in order to obtain a sharp, high resolution, image there are occasions when there is no advantage in doing so.

A classic example is where an image is formed onto a digital camera, such as a Charge-Coupled Device (CCD). The active area of a CCD camera typically consists of a two-dimensional array of very small detectors, usually known as 'pixels' and is a very convenient way of transferring an image directly to a computer for desktop publishing or image processing.

An ultra-high resolution optical system may be used to form the image on the camera but this will be to no avail if the pixels in the camera are larger than the resolution of the optics. As a general guide the pixel size of the camera should be about one half of the optical resolution, so as to give sampling of the image at the 'Nyquist rate'.

The optical resolution, R, of a diffraction-limited lens is given by

$$R = \frac{0.61 \cdot \lambda}{NA} \quad (1)$$

where NA is the Numerical Aperture of the lens and λ is the optical wavelength.

The spatial resolution at the image plane of the lens, Ri, is given by

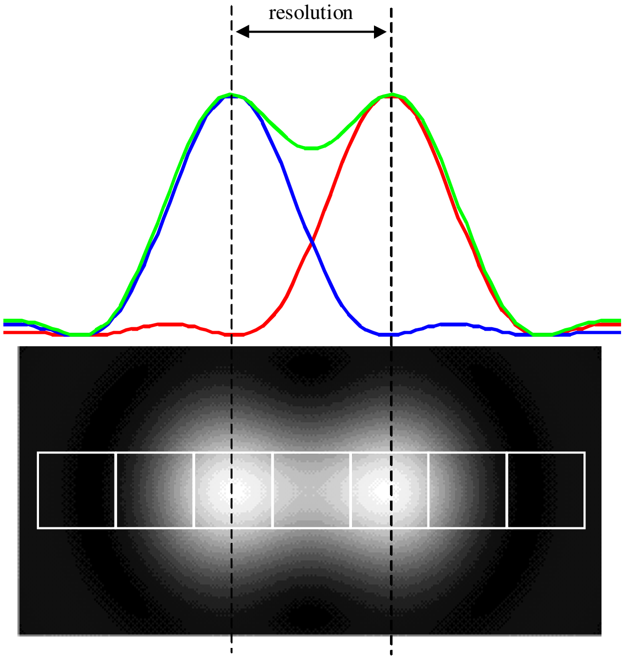
$$Ri = R \cdot M \quad (2)$$

where M is the magnification of the optical system.

Thus, the required pixel size of the camera, P, is given from (1) and (2) by

$$P < \frac{0.61 \cdot \lambda}{NA} \cdot \frac{M}{2} \quad (3)$$

As an illustration, the diagram below shows intensity plots of the diffraction patterns from two adjacent object points that are separated by the optical resolution of the system, known as the Rayleigh limit:



The squares superimposed on the image represent the pixels in the camera. Here it can be seen that the centre pixel will register a slightly lower intensity level to those on either side of it, thus the two objects are said to be 'resolved'.

Clearly, increasing the magnification of the image, which is the same thing as making the effective size of the pixels smaller, does not improve the resolution – it simply smears the diffraction patterns across more camera pixels, this is known as 'empty magnification'.

The only way to improve the resolution is by increasing the NA while adjusting the pixel size and/or magnification to maintain the inequality given in (3).

As a real-world example, consider the case of a microscope objective where the NA of the lens might be 0.90 and the magnification x50 then, from (3), the pixel size should be less than about 9um, which, conveniently, is a typical size for a medium resolution CCD camera. Clearly if a camera with smaller pixels is used then no extra information about the image will be gained at the given magnification unless the NA of the lens is also increased.

Interestingly, a similar situation exists within the human eye. The diffraction limited resolution of the human eye, which is determined by the pupil diameter and the focal length of the eye-lens, is approximately equal to the distance between the light sensors at the retina, known as the 'cones'. It is sometimes found, however, that in reduced light levels, when the pupil is wider than for bright light, the resolution is in fact less than expected. This is due to residual aberrations in the eye-lens becoming increasingly significant as the pupil widens.