

HOW MANY PIXELS DO YOU REALLY NEED?

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When buying a new digital still camera the first question is about the number of pixels. How good the image quality really is, does often not only depend on the number of pixels, though. It also depends to a big extent on the optics, mechanics, and further factors. But how can one judge about the right amount of pixels? This paper will provide some information about the image quality and optical limitations, depending on the pixel size.

Today, especially for consumer cameras, the number of pixels increases. A few years ago 1 up to 3 megapixels were common, today it is often 6 to 11 (or more) megapixels. The pixel size itself decreases, partly due to improvements in the layout but furthermore due to cost reasons from the silicon. This cost advantage is followed as well in machine vision. But going to smaller pixels is related to some disadvantages or at least, some points that have to be taken into account. Many applications for image processing still run perfectly with VGA resolution, now going to approximately to 1.4 megapixels, but depending on the framerate.

Small Pixels Effect Signal to Noise Ratio and Dynamic Range

If a pixel gets smaller, the photosensitive area is reduced. Because the surrounding microelectronics cannot shrink with the same ratio, the photosensitive area has to be reduced even more. But the smaller the pixel itself is, the fewer electrons can be collected. The maximum amount of collected electrons is called full-well capacity. If you do not make use of the full-well capacity, but will limit the maximum amount of electrons to a certain level, it is called saturation capacity. Only the saturation capacity will give the limit for the maximum signal to noise ratio (SNR). The square root of the captured electrons shows the physical limit of noise. So, the maximum SNR is square root of the saturation capacity. For many CCD sensors the max SNR is between 100 and 150, according to 40 to 44 dB, respectively ($\text{dB} = 20 * \log(\text{SNR})$).

A second parameter for a camera is the dark noise and the related dynamic range. If the signal is in the same level as the dark noise, it is called detection limit or sensi-

tivity. Dynamic range is the ratio between dark and bright, between dark noise and saturation capacity. Good CCD cameras without Peltier cooling will achieve about 7 to 10 electrons, but even 20 electrons is still an acceptable standard. For a good camera with 20000 electrons saturation and 8 electrons, the dynamic range covers a factor of 2500, equal to 68 dB or 11.3 bits (1 bit = 6.02 dB).

Optical Limitations

But how large does a pixel have to be to catch the resolution of the lens that projects the object to the sensor's plane? Let's start with a very tiny spot on the object. The light has to travel through a couple of lenses. All the lenses will correct for deviations a single lens will have, like spherical aberration, coma, astigmatism, field curvature, distortion, and dispersion. Good lenses have a spot size of five to seven microns, very good lenses might achieve even below five microns. Cheap lenses might blur up to 15 or 20 microns. But even if the corrections will be perfect, there is a physical limitation: diffraction. As a rule of thumb, the F-number can be taken in microns to get the diffraction limit in the sensor. Like an F-number of 5.4 will have a spot size of 5.4 microns on the sensor as the best you can get.

$$\phi_{\text{AIRY}} = 2.44 * k * \lambda$$

(with λ = wavelength and k = F-number = f/d ,
with f = focal length, d = diameter of iris)

Modulation Transfer Function (MTF)

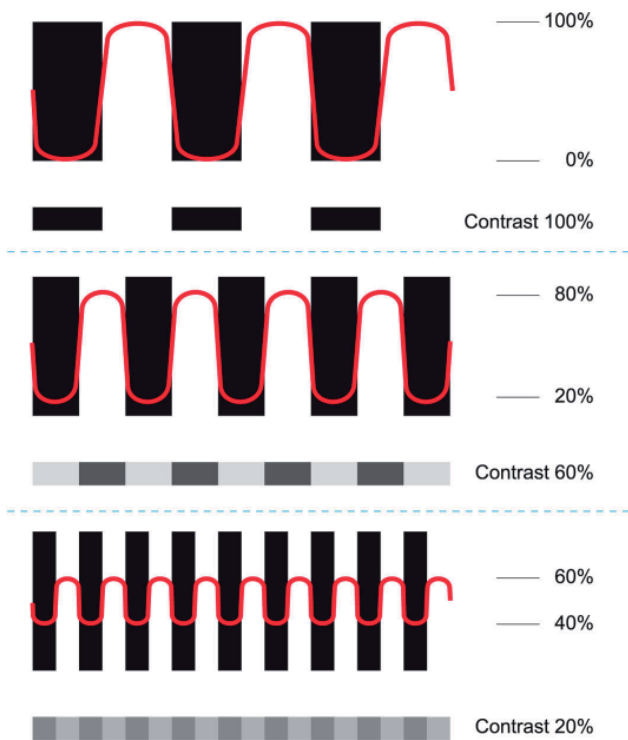
When reading specifications you will often hear of the Modulation Transfer Function (MTF). This is comparable to a test for your eyes at the oculist. The test starts with huge letters and will turn to smaller and smaller letters. The smaller the letter, the higher is the line density per millimeter. At one point you are not able to resolve the lines of the small letter; it will turn gray.

To test a lens and a camera, tests will start with a black and white stripe pattern. The light will pass through the lens. Depending on the lens' quality the projected image on the sensor will be either sharper or more blurred.

The more linepairs per millimeter (lp/mm) the less the contrast between black and white will be. The contrast is measured as:

$$\text{Contrast} = (\text{Max} - \text{Min}) / (\text{Max} + \text{Min})$$

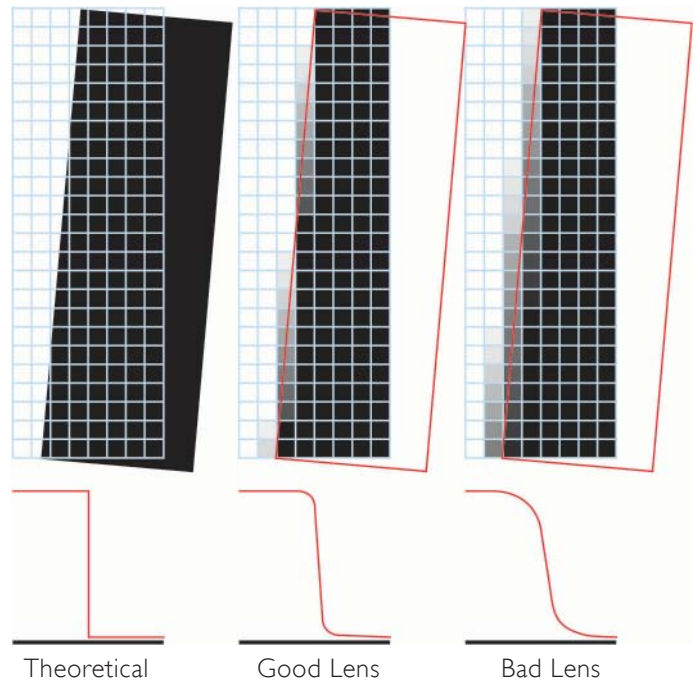
As demonstrated in the figure, the upper pattern has a contrast of $(100\% - 0\%) / (100\% + 0\%) = 100\%$, the middle of $(80\% - 20\%) / (80\% + 20\%) = 60\%$, and the lower one of $(60\% - 40\%) / (60\% + 40\%) = 20\%$.



Finally the MTF is a diagramme that gives the contrast in dependence of the number of linepairs per millimeter. The MTF varies over the field of view and depends on tangential and sagittal orientation of the pattern. Professionals can judge quickly whether the lens fits to the application or not.

How can I Decide if I Have Chosen the Right Lens?

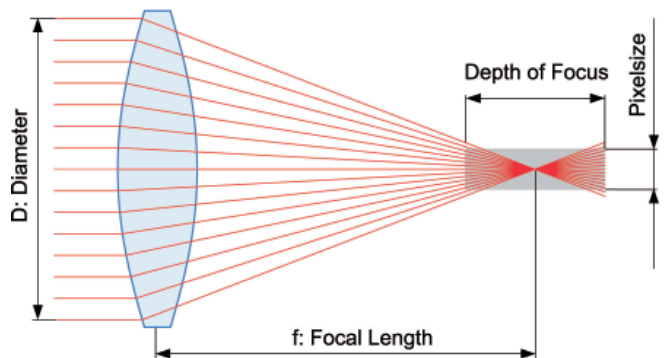
To figure out whether the used lens fits to the resolution given by the pixelsize, a black to white transition has to be projected onto the sensor. The transition has to be slightly rotated by a few degrees. If you zoom into the image, the different grey values depend on how much black and how much white is on the pixel. In the middle drawing you can see the grey scale. A good lens will give you nearly black, when the neighbour pixel turns white. On the right drawing, the lens does not fit to the pixel resolution. This is an easy tool to decide whether the lens fits to the pixel size.



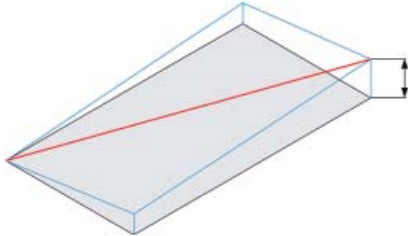
Depth Of Focus (DOF)

With small pixels we do not only have special requirements to the optics. There are as well tolerances that have to be fulfilled in respect to the mechanical alignment, such as the flange, the mechanical interface, and to the tolerances for the sensor positioning for all six degrees of freedom (x, y, z, tip, tilt, and rotation). With ten micron pixels and an F-number of 2.8, the maximum tilt over the whole sensor is ± 28 microns. With a pixelsize of five microns, it is only ± 14 microns. If the iris is opened to 1.4, the range for tilt will halved once more. Depth of focus (DOF) or maximum tilt is limited by:

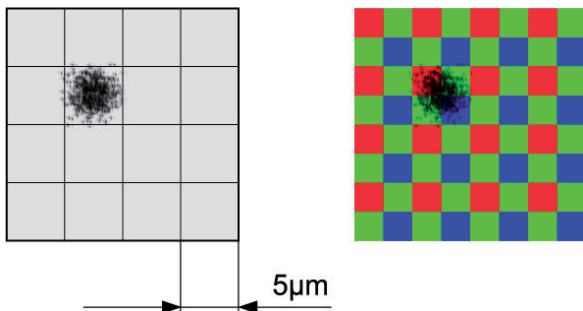
$$\text{DOF} = 2 * k * \text{Pixelsize}$$



This will finally result in a very precise alignment of the sensor in respect to the flange. Especially for machine vision applications in semiconductor and electronics a very low tolerance in tip and tilt is needed.



As we can summarize at this point, there is a limitation for the pixel size. Sizes below five microns for monochrome cameras start to get in a range where more pixels are present, although the optics is not able to resolve this. In case of color cameras, mainly using a Bayer pattern (red, green, red, green, red, ... for odd and green, blue, green, blue, green, ... for even lines) will double the effective pixel size, because to capture the full red, green, and blue (RGB) information, a 2 x 2 pixel array has taken into account.



Data Compression

Machine vision applications usually work with raw, uncompressed data. A full RGB image has to be transferred to the computer, and then to be analyzed. Therefore the number of pixels that is common for commercial digital still cameras is not valid for machine vision cameras. With a Camera Link interface it is possible to provide more than 200 full frames per second with a 4 megapixel camera. The data stream is equivalent to more than one CD per second (full of data). So, many machine vision applications often only use VGA resolution (640 x 480 pixels) with a low frame rate. High end applications are forced to go to higher resolutions and higher frame rates.

Summary

It is difficult to give a limit or recommendation how many pixels are really required. For machine vision the number of pixels is often less compared to digital still cameras. It depends on the application. In most cases a VGA resolution or a megapixel camera will do a perfect job. Nevertheless the pixel size seems to be much more important. In case of monochrome cameras a limit of 5 microns makes sense, for color cameras with a Bayer pattern 2.5 microns are acceptable. Small pixels affect as well the signal to noise ratio and the dynamic range.

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