Maximizing Depth of Field

Depth of field ("DOF") is the distance range in which an object is in focus. When an object is too close or too far from a camera lens, the image of the objects gets blurry. The depth of field is the difference between the furthest point and nearest point at which the object is in focus.

It is not uncommon for the distance between a lens and the object being imaged to vary. Consider:

- One object having multiple surfaces, each a different distance from the camera. This is common when inspecting machined parts.
- Multiple object types either imaged within the same frame, or imaged in quick succession. For example, imaging cartons from above a conveyor when carton height varies.
- Objects presented to the camera at varying distances. Imagine imaging the side of objects traveling on a wide conveyor.

In all of these scenarios, depth of field is an important design factor.

So what determines the depth of field? There is a lot of misinformation on this subject. Some people will recommend a lens having a shorter focal length, because that will image a larger area, which increases the depth of field. But in machine vision, a larger field is usually not a good option. Other people will recommend a lens having a longer focal length, because that will increase the working distance, putting the focus nearer what photographers call the "hyper-focal distance." But, as it turns out, neither a shorter nor a longer focal length is the answer for machine vision installations.

DOF Equation

Depth of field can be calculated with the following equation (assuming a high quality lens operating at the diffraction limit.)

$$DOF = (2 \times C \times EF) / B^2$$

In this equation, DOF is the depth of field, C is the "circle of confusion", EF is the effective focal length, and B (beta prime by convention) is the magnification factor. Let's consider each factor in turn.

Circle of Confusion

The circle of confusion is, for our purposes, the camera's pixel size. We assume the camera resolution was carefully chosen such that every pixel matters.

Magnification

The magnification factor is the ratio between the size of the camera's sensor and the size of the field of view. For example, in microscopy, the field of view might be just 3.0 mm wide, and the camera's sensor could be 8.6 mm wide. The magnification factor is then 8.6 / 3.0, or 2.87. Typically in machine vision we're working with magnification factors between about 0.02 and 4.0.

Effective f#

Lens manufacturers typically specify a lens's f# when it is focused on infinity. Since this usually is not the case in machine vision, it's helpful to consider "effective f#", or "EF". EF is the manufacturer's f# adjusted for the magnification factor when focused nearer than infinity. It's important to consider EF, instead of the manufacturer's f#, when imaging objects relatively close to the lens. The equation for calculating EF is: EF = (f#)(B + 1) where f# is the f# specified by manufacturer at infinity, and B is the magnification. For example, if the magnification is 0.5 and the manufacturer's f# is 4, then EF is 6.

Focal Length

Note that the lens's focal length isn't in the equation. Neither a shorter nor a longer focal length is the answer. Yes, the focal length helps determine the magnification factor. But, in machine vision, the magnification factor is driven by the necessary field of view and the camera sensor size. The focal length is how we get the necessary magnification, and the magnification is generally fixed by application requirements. (More on that later.)

Maximizing DOF

So, using the DOF equation above, how can we maximize DOF? From the equation, we can see that increasing C (pixel size), increasing EF (effective f#), and decreasing B (magnification) will each increase DOF.

Increasing Pixel Size

The benefits of larger pixels are many. In addition to increasing the depth of field, larger pixels:

- Gather more light, helping to offset the darkness resulting from closing the lens aperture.
- Generally have a greater full well capacity, resulting in greater dynamic range.

- Are more immune from the cross-talk associated with very small pixels.

There are two disadvantages of larger pixels. First, holding resolution constant, larger pixels mean a larger sensor, which means greater magnification. And greater magnification reduces the depth of field. Second, cameras with larger pixels generally cost more to purchase.

Larger pixels can be simulated by binning pixels together. Binning pixel values in a 2 x 2 matrix doubles the “circle-of-confusion”, which doubles the depth of field. This also enables doubling the f-number, which doubles the depth again, quadrupling the total depth of field. This of course assumes that you can get by with less resolution.

Decreasing Sensor Size

Decreasing the size of the image sensor will increase the depth of field. Assuming we need to hold image resolution constant, this will mean smaller pixels, which seems contrary to the discussion above about pixel size.

Assuming we need to hold sensor resolution constant, smaller pixels are needed. The smaller pixel size (circle-of-confusion) works to decrease the depth of field, but the shorter focal length needed to deliver the same field of view actually results in a net improvement in the depth of field. (This is one of the very few instances where smaller pixels have an advantage.) Note that smaller pixels collect less light and, once again, brighter illumination and/or longer exposure time may be needed.

Increasing f#

Any professional photographer will tell you that closing the lens aperture (increasing the f#) will increase the depth of field. In fact, photographers often decrease the f# to make the background behind their subject blurry – just the opposite of our goal. So increasing the f# appears to be an easy way to increase DOF.

But what else happens as the f# is increased? The image gets dark. And there are only two good ways to compensate for this. First, sometimes the camera’s exposure time can be increased. Other times it cannot because the object is moving quickly, and the increased exposure would introduce unacceptable blur. The second method is to increase the intensity of the illumination.

f# and Diffraction Limit

Doubling the f# will double the depth of field. However, as the f# is increased, the diffraction limit will start to degrade image quality. An in-depth explanation of the diffraction limit is beyond our scope, but we can learn from the following equation: DL = 2.44 x λ x f#, where DL is the diffraction limit, λ is the wavelength of light, and f# is, well, the lens f#.

When DL becomes larger than our camera's pixels, image quality suffers. To determine when this occurs as we close the lens aperture, rearrange the equation to solve for f# and substitute the camera pixel size for DL. We then have f# = P / (2.44 x λ), where P is the pixel size. For example, assume a camera has 4500 nm pixels and a 660 nm red light. If we set the f# greater than just 2.8, the diffraction limit will introduce fuzziness. The greater the f#, the more fuzziness. As we close the lens aperture further, the depth of field becomes the least of our problems!

For a given f#, there are only two means of keeping the diffraction limit from compromising image quality. First, if at all possible, use a light having a shorter wavelength. In the previous example, using 440 nm blue light would result in hitting the diffraction limit at f4.2, instead of f2.8. Second, use a camera having large pixels. Continuing the example, a camera with 5.86 µm pixels would further extend the diffraction limit from f4.2 to f5.5.

Decreasing Magnification

In the DOF equation, magnification is squared in the denominator. This is mitigated by the presence of magnification in the numerator, where EF = (f#)(B + 1). Nonetheless, reducing the magnification will greatly increase depth of field.

The problem is how to go about reducing magnification. Our options include:

- Increasing the field of view. This means living with less pixel resolution (more object space mapped to each pixel) and the image processing precision may suffer.
- Decreasing the camera sensor size. See the topic above about this.

The only means of reducing magnification while holding pixel size constant is to reduce image resolution, which is unacceptable in many machine vision projects.

Summary

The world of optics is full of compromises. When working to maximize an imaging system's depth of field, it's easy to start chasing your tail. You want larger pixels, but that means a larger sensor with greater magnification, and that means less DOF. You want a high f#, but you easily hit the diffraction limit and the image is fuzzy despite technically having an improved DOF. Maximizing DOF is especially challenging when imaging small objects, moving quickly, using a high resolution camera.

Nonetheless, the following suggestions will help:

- Do not image using more resolution than absolutely necessary. Using more pixels than needed will reduce the DOF, either due to smaller pixel size, or higher magnification.
- Choose a camera having a smaller image sensor, understanding the associated consequences.
- Use a bright light, especially when imaging objects moving quickly. This is necessary for sufficient illumination when the aperture is small.
- Don't reduce the f# far beyond the diffraction limit. The next suggestions are really about avoiding this limit.
- Use light having a short wavelength, such as blue, if appropriate for your task.
- Use a camera having larger pixels.

Experimentation is often required to balance these many factors in such a way that system outputs meet your goals.

About the Author

Brian Durand has twenty-five years of experience building machine vision systems. He has successfully developed automated solutions for visually inspecting everything from packaging materials to implantable medical devices. Durand is an A3 Certified Vision Professional, Advanced Level.

Machine Vision Store
Trusted Vision Solutions.

Revision 20230929