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LIGHT IDEAS #2: How Do I Make a Telecentric System?

So what's the big deal? Why are so many people talking about telecentric lenses these days? Well, as vendors will tell you, a couple key advantages of a telecentric system are constant perspective across the field as well as large depth of field in terms of focus *and* magnification.

What we will explore here is how to make and use a telecentric system with common optics. Why? Probably the most important reason is flexibility. Despite the range of available products, commercial systems are pretty limited in terms of magnification and stand-off distance. The second big reason is cost savings. A "home built" system can be much less expensive than the commercial variety.

Now there is *always* a trade-off. Remember TANSTAAFL – There Ain't No Such Thing As A Free Lunch. The type of system described here generally won't have the same level of optical performance as the commercial ones. In many cases, however, the camera detector is a performance bottleneck long before the optics. Additionally, there are modifications you can make to the design discussed here that can significantly increase performance.

So what's first? The basic idea behind a telecentric system is to place a limiting aperture at the back or front focus of a lens. By definition of a lens focal point, F, this allows only light rays that are parallel to the lens optical axis to enter or leave the system. Sometimes this aperture is called a telecentric stop. Figure 1 shows the case for an aperture at the back focus, F′, of a lens whose focal *length* is f. Light comes from an object (not shown) at the left. Non-parallel rays (grey) are blocked.

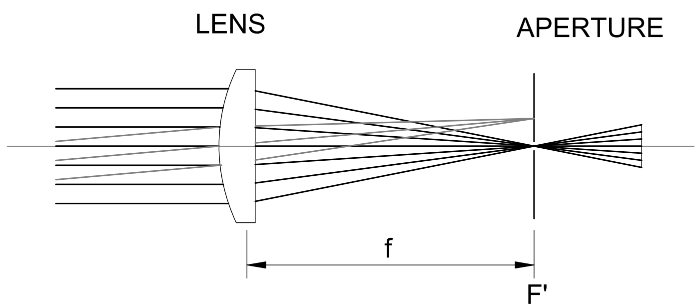

Figure 1

After the aperture or stop has been placed at the back focus of the lens, you may proceed with calculating object and image distances for a given magnification as usual. This arrangement, however, is severely limited and can take up a lot of space for long focal length lenses or small magnifications.

An arguably better way of setting up a telecentric system is to use two lenses. There is more than one way to do this as well, but only one method will be discussed here. Figure 2 shows the arrangement which has great flexibility.

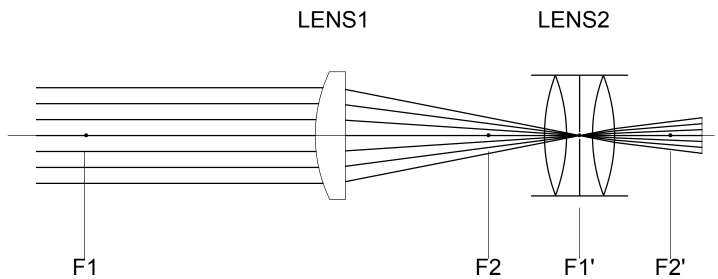

Figure 2

Here F1 and F1′ are the front and back foci of LENS 1. F2 and F2′ are the front and back foci of LENS 2 which is shown to be complex such as a camera or photographic enlarger lens. Note that it is the iris (aperture) of LENS 2 that serves as the telecentric stop of the system. The smaller this aperture (larger f-number setting), the fewer non-parallel rays are allowed to enter. Or you can say the system becomes more telecentric.

Generally the most compact systems with the best imaging are achieved by choosing your lens focal lengths in the same ratio as the absolute value of your desired magnification. Suppose you want a magnification of -0.33. Choosing LENS 2 as a 40mm fl. enlarger with LENS 1 a 120mm fl. doublet will produce a focal *ratio* of 0.33 and the desired *magnification* when the object is exactly at F1 and the image is at F2′. This is a good start.

Of course it's likely that you won't be fortunate enough to find exact focal ratios for every system you want to build. Even if you can, it's not practical to buy lenses for every combination. The following two equations, along with reference to Figure 3, may be used with this type of system to calculate object and image distances for any magnification once you know which lenses you'll be using. The derivation isn't shown here (we *try* to avoid boredom), but they're just based on the Newtonian form of the lens equations as discussed in Light Ideas #1.

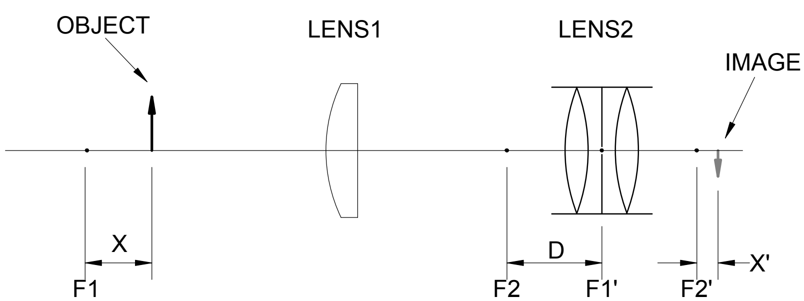

Figure 3

Figure 3 shows a layout similar to Figure 2, but with added variables, and an object and image. The light rays have been removed for clarity.

1) $x = \dfrac{f1 \cdot (f2 + M \cdot f1)}{M \cdot D}$ 2) $x' = \dfrac{(f2^2 \cdot x)}{(D \cdot x - f1^2)}$

Where:

f1 = Focal length of lens 1
f2 = Focal length of lens 2
M = Overall signed magnification
D = Distance, measured left to right, from F1′ to F2.

As shown, D would be *negative*.

x = Object distance, measured left to right, from the object to F1. As shown, x would be *negative*.

x′ = Image distance, measured left to right, from F2′ to the image. As shown, x′ would be positive.

So, using the 40mm fl. and 120mm fl. lenses, suppose you want to set up a system with a magnification of -0.35 instead of -0.33. What will your object and image distances be? Just "plug and chug" as the saying goes. The one *slightly* esoteric value you need, D, is just the distance from the front focus of Lens 2 to its own aperture or entrance pupil. If this value isn't available from the vendor, you can find the front focus experimentally by using the method described in Light Ideas #1. It will *often* be nearly the same magnitude as the focal length of the lens itself, and that's good for a rough estimate. In this case, a 40mm fl. Nikon EL-Nikkor lens has a D value of -36.6mm. Using these numbers the results are:

$$x = -18.7\text{mm}; \qquad x' = 2.2\text{mm}$$

You can check that there would only be a slight difference if D had been set to -40mm.

This example assumed using a doublet for Lens 1, though singlets may be used as well. Performance, however, is generally much better with an achromatic doublet, especially with spectrally broad band illumination – white light. In any case, the lens should be one designed for use at an infinite conjugate ratio and the infinite conjugate surface should be towards the object. Cutting through the optical jargon: When using a singlet, it's best to use a plano-convex lens. With a singlet or a doublet, place the most curved surface towards the object. If using a Fresnel lens, it's typically best to place the grooved surface towards the object. There are exceptions, so check with your supplier to verify the infinite conjugate.

The results from a telecentric system can be fairly amazing. If back lighting is possible, a collimated source is especially useful and efficient. You can detect some pretty small refractive variations in transparent media this way.

The downside of the type of telecentric system described here is that field curvature and distortion may be a problem, even with a doublet. The large depth of field with a small aperture generally overcomes field curvature considerations. The distortion, if significant, will at least be constant and so may be corrected in software with a look up table for critical gauging applications. Also, the addition of even one properly designed singlet lens can often improve a system to near diffraction limited performance. But that's a subject for a different time.