Put in Perspective

Optical Metrology Basics: Telecentric Lenses

Conventional lenses for industrial image processing are "entocentric" with image formation in central projection. This perspective often is quite a nuisance for metrology. Telecentric lenses are designed for parallel projection and thus eliminate the warping produced by central projection. This article explains the concept of telecentric imaging.

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Conventional Lenses

The typical task in industrial image processing is to view a conveyor belt with a camera mounted directly above, producing a sharp image of an object in the detector-plane by means of a standard-lens. The lens may be treated as a simple single thin lens for rough calculations of basic parameters like the field of view, the format of the sensor, the focal length or the distance between camera and object. The object, however, will only be in focus, when focal length, object distance and image distance obey the lens formula. When two of these parameters are fixed, the third parameter is unambiguously determined by the laws of optics. The well-known simple lens equation for the paraxial approximation usually is well suited and quite sufficient as the first step for the optical layout of an image processing application [1]. With a conventional lens, the object can be brought into focus by slightly moving a part of the lens along the optical axis, thus choosing the proper image distance and producing a sharp image. For many applications, adjusting the focus ring is sufficient to reach the milestone for the optical part of the project. What happens, however, when oscillations of the conveyor-belt occur during production and the image processing has to deal with a considerable range of object distances? Three-dimensional objects like holes, tubes, screws, bolts or springs per se have structures at different distances and will inevitably confront the application engineer with more complex optical effects in imaging. In this situation, two effects occur: the image will be blurred, and the image height will change with the distance. Both phenomena may lead to problems when the dimensions of objects are to be measured by image processing.

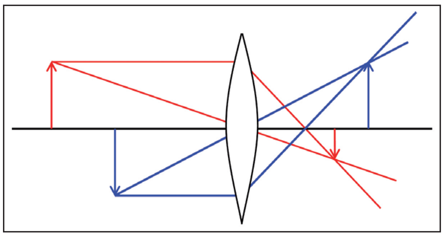

Fig. 1: For conventional lenses, the image size depends upon the object distance

Simple Lens Equation

To get a better idea of the situation, we first look at two identical objects positioned at different distances from the lens. Figure 1 shows a red and a blue arrow of the same length, both based on the optical axis, but pointing in opposite directions perpendicular to the optical axis. For each of these arrows the position of the sharp image can simply be constructed geometrically by tracing only two rays. Rays, which enter the lens parallel to the optical axis, will pass through the focal point on the optical axis. Rays, which aim at the center of the lens, will exit the system without changing their direction. For the construction of the image, the tip of the arrow is used; the sharp image of the tip is the point, where these two construction rays intersect. The same construction is possible for the center of the arrow, leading to the observation that the image is formed in a plane perpendicular to the optical axis. In particular, the base of the arrow is imaged back to the optical axis. The construction immediately shows that the two arrows, although having the same height, will produce images of different heights, the smaller image corresponding to the larger distance. The magnification, that is the ratio of image height and object height, is different for the two positions, it depends upon the object distance. The two corresponding sharp images, however, will not only have different heights, but will also appear in different image distances. When the object distance varies, such as in the scenario mentioned above, re-focusing would be necessary to obtain a sharp image. Only special applications allow for such a procedure. Usually, image processing on the factory floor will choose a fixed image plane and will be quite happy with a clamping device at the lens body to secure focussing, humbly looking at some blurred images for objects outside of the specified object distance range.

Figure 2 shows how a blurred image can occur in a fixed detector plane when the object is moved away from the proper object distance. The geometry of the situation is the same as in figure 1, and the positions of the images for the red and the blue arrow are already known from the previous construction. In figure 2a, only the base points of the arrows are shown. Their images are formed by a cone of rays which can enter the lens through an aperture which may even be just the lens mount. We assume that the detector is positioned in the image plane for the blue arrow. The rays for the red arrow which come from a larger distance will intersect in front of this image plane and will reach the detector as a divergent bundle, thus producing a small disc as an image instead of a sharp point. The same holds true for an object-point which is not on the optical axis like the tip of the arrow as shown in figure 2b. The whole image of the red arrow on the detector will thus be blurred due to this geometrical effect. A closer look to figure 2b shows that this image will be smaller than the image for the blue arrow which is in proper focus. We thus will expect that an object will appear smaller and smaller when it moves away from the camera even with a fixed detector plane – we may easily verify this fact within a minute in every laboratory where a camera is mounted on a vertical Kaiser-stand with height adjustment by a hand crank. As an alternative, we might just take a break, gazing off into distance with eyes wide open, and think about what we see: our eyes basically are entocentric lenses in this situation. For quantitative calculations, however, more elaborate methods of technical optics are required. The simple lens equation is not sufficient for this task. In particular, the influence of apertures and diffraction effects has to be taken into account [2].

Central and Parallel Projection

Imaging with a conventional entocentric lens is a central projection. This is illustrated in figure 3, where both objects from figure 1 are drawn in both distances, and the image

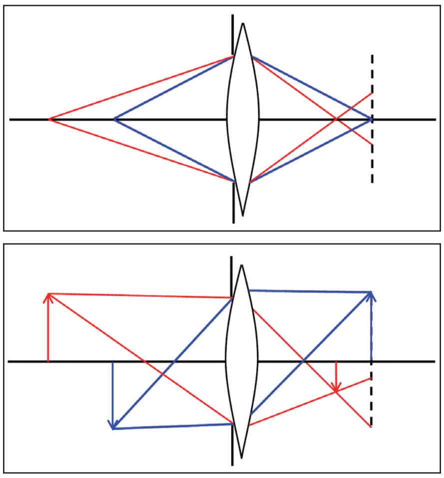

Fig. 2: A detector placed at the image plane of the blue arrow will see a blurred image of the red arrow; figure 2a shows the image formation for the base point, figure 2b for the tip of the arrow

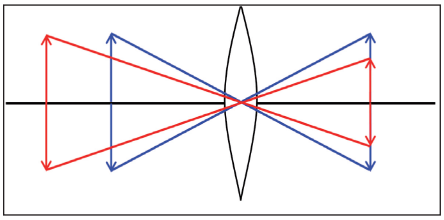

Fig. 3: Imaging with a conventional lens is a central projection

formation is shown for the cone of rays which pass the center of the lens. It is quite evident that the height of the image depends upon the object distance in central projection. Parallel projection would eliminate this effect. We thus need an optical arrangement with image formation by those rays only which enter the system parallel to the optical axis. For a simple thin converging lens, all the rays traveling parallel to the optical axis are focused to the focal point on the optical axis – this is just the basic definition of the focal point. A small aperture, centered in the rear focal plane, will thus block all those rays which did not enter the system parallel to the optical axis, and the image will be formed with the remaining rays. Fig. 4a shows this arrangement: the concept of an object side telecentric lens. It can be shown that the image size for a fixed detector plane remains constant for this system even when the object distance is changed [2]. Since the diameter of the aperture must not be reduced to just a pinhole for reasons of intensity, the telecentricity can only be achieved in approximation. Telecentric lenses are usually designed for a fixed working distance and have a defined telecentric range around this distance. Within this range, the remaining variation of the magnification is specified. For a good telecentric lens, e.g., the image size may vary by just 1 µm over the whole field. When this precision is to be fully exploited for gauging, it makes sense to optimize all the other optical parameters of the lens. The remaining distortion at the image plane is an important source of uncertainty of the measurement. For this reason, telecentric lenses are usually very well corrected and are specified with distortion of much less than 1 percent.

Bilateral Telecentricity

With an object side telecentric lens, the magnification will remain constant for a fixed position of the detector plane perpendicular to the optical axis only. Even a small tilt of the image plane may result in changing image heights for an object moving away from the lens. Since the rays hit the image plane as a divergent or convergent bundle at oblique incidence, the intensity distribution of edges of objects may become asymmetrical. Methods with subpixel-precision are often reasonable in conjunction with telecentric imaging, where the remaining changes of the image size are just fractions of the pixel pitch. Subpixel-algorithms, however, may be quite sensitive to asymmetries in the edge profile. A lens system with two stages can eliminate these disadvantages. For this purpose, the aperture is placed in the front focal plane of a second lens, which projects the aperture to infinity, thus producing rays leaving the system parallel to the optical axis. This concept is illustrated in figure 4b. It can be shown that the image size for this arrangement remains constant even when the detector plane is not fixed; it is insensitive against defocusing [2]. The magnification in this case is the ratio of the focal lengths of the two lenses. Such bilateral telecentric lenses are available with a mechanical means for re-focusing and thus allow for the adjustment of the working distance to the requirements of the application. In general, this concept is quite similar to the Kepler telescope, but with the main difference that the bilateral telecentric lens uses only those rays which enter the system parallel to the optical axis. This directly leads to a very important restriction for applications with telecentric lenses: for imaging in parallel projection, the free diameter of the lens has to be larger than the object itself. For large objects with dimensions of several feet like in web inspection, e.g., a single telecentric lens neither will be available nor be an economical approach. A phalanx of staggered smaller telecentric lenses with overlapping fields of view usually provides a reasonable alternative. Due to their optical layout, telecentric lenses are longer compared to conventional lenses [3], may have a mass of several kilograms, will usually require high brightness lighting, and are quite expensive. For precision measurements of dimensions in image processing, however, these masterpieces of technical optics are often mandatory.

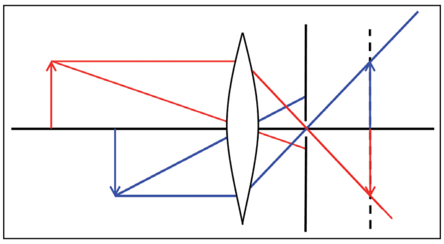

Fig. 4a: An aperture in the focal point results in an object side telecentric lens; for the fixed detector plane the magnification is constant for different object distances

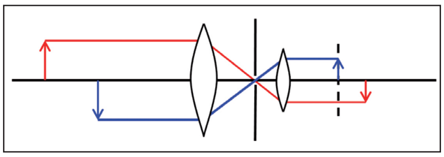

Fig 4b: In the bilateral telecentric system, the image size does not depend upon the position of the detector plane

References

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