In optical metrology applications, telecentric lenses – in contrast to fixed focal length lenses – have the advantage that they provide correct measurement results even when the distance to the object varies.

The perspective decides

Telecentric lenses have some advantages compared to lenses with fixed focal length.

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How do telecentric lenses work? And how do they differ from fixed focal length lenses? This article explains why telecentric models are predominantly used in optical metrology.

Similar to human vision, fixed focal length lenses (also referred to as entocentric lenses) have an angular field of view, resulting in objects further away being imaged smaller and vice versa. In a metrology setup, this property is undesirable because the measurement result, e.g., the diameter of a component, is not meant to change even if the test specimen is positioned within a certain tolerance range in front of the test system. With this so-called parallax (or perspective error), the magnification changes depending on the working distance. In telecentric lenses, this undesirable property is eliminated or greatly reduced by their design. If two identical objects are at different distances from the measurement setup, the difference becomes negligeable (**Fig. 1**): Despite the different distances of the cubes, the telecentric lens displays them at the same size. With the fixed focal length lens, the closer object appears larger than the more distant one. Telecentric lenses achieve this independence from the working distance by having the main beam parallel to the optical axis. This is their crucial feature. However, to do so, the first lens element must be at least as large in diameter as the workpiece to be inspected itself.

Depth of field

It is often mistakenly assumed that telecentric lenses have a greater depth of field than fixed focal length lenses. Ultimately the depth of field

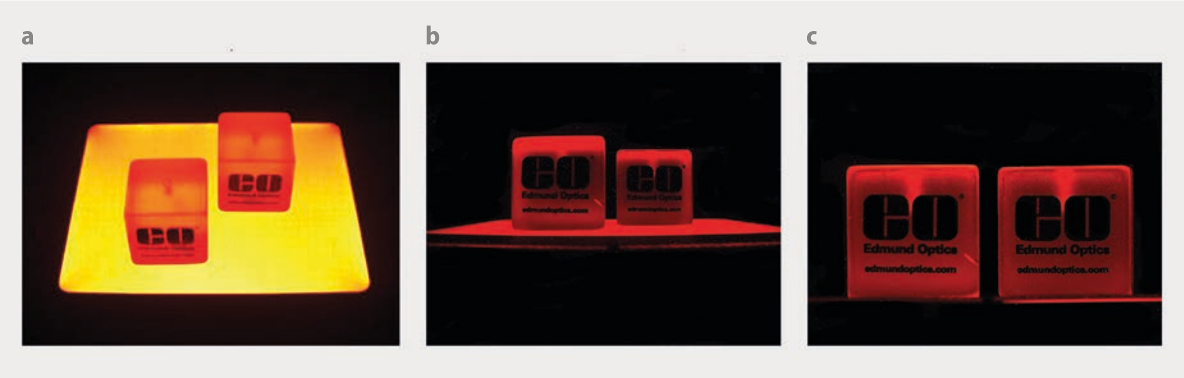

Fig. 1 The two cubes are identical, but have different distances to the camera (a). Due to the aperture angle of the fixed focal length lens, the right cube is imaged smaller than the cube that is closer to the inspection system (b). In the same scene taken with a telecentric lens both cubes are the same size (c).

is determined by the *f*-number of a lens; telecentricity only has an indirect impact. The *f*-number is, among other things, decisive for the diameter of the lens. This diameter is large with telecentric optics compared to a fixed focal length lens, all other parameters being equal. Therefore, it is common for telecentric lenses to start only at *f*-numbers of about *f*/6. This is to reduce the diameter, design complexity, but also the cost of a telecentric lens. Fixed focal length lenses can often be opened up to *f*/1.4 – which is unattainable for telecentric lenses.

When comparing the *f*-numbers of telecentric and entocentric lenses, it is easy to confuse two parameters. For fixed focal length lenses, the value usually engraved on the lenses denotes the image space *f*-number for infinite working distance. This choice makes sense for several reasons: pragmatically, the fixed focal length lenses can be used over a large range of working distances and there is no other 'universal' working distance that is applicable to all lenses regardless of focal length or manufacturer. For telecentric optics, the working distance is finite and fixed. Accordingly, in order to ensure comparability, a parameter known as working *f*-number is used. It is calculated by weighting the theoretical *f*-number based on infinity with a factor that depends on the specific magnification of the respective lens. For a correct comparison with the *f*-number of a fixed focal length lens, the value engraved on this lens must be converted by the same factor.

Another interesting property of telecentric lenses favours them compared to entocentric optics in some applications. Due to the lack of perspective, objects become uniformly blurred when you reach or go beyond the limits of depth of field. If you look at a round object with telecentric optics and leave the focus area, the object will become symmetrically blurred (**Fig. 2**). An algorithm can therefore still determine the correct position of

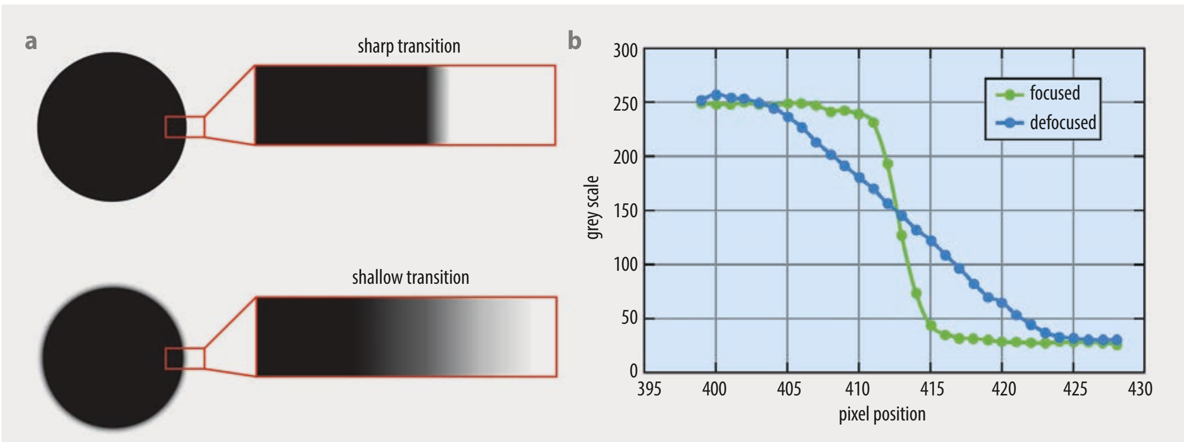

Fig. 2 A telecentric lens depicts a point differently measured in focus (a, above) or with a slight defocus (below). The effect of defocus is distributed symmetrically. The course of the grey scale (b) shows that the edge is distributed over several pixels in the defocused case (blue), which can lead to more repeatable results than in the focused case (green).

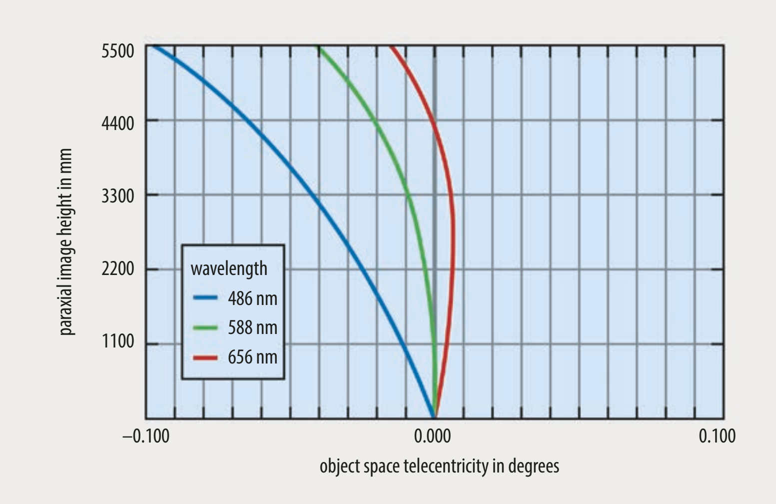

Fig. 3 The example of a 1X lens shows that image height and telecentricity depend on each other differently at varying wavelengths.

the center of mass. Lenses with fixed focal length would distort the object asymmetrically into an ellipse depending on its position in the image and prevent it from determining its exact position. It is possible to extend the nominal depth of field in special situations without necessarily reducing the quality of measurement results. Depending on the application and algorithm, it may even be advantageous to work with a certain amount of blurring. If the transition of an edge is distributed over several pixels instead of only two, a measurement system may provide more repeatable results.

Telecentricity – quantitatively

In data sheets, telecentricity is often specified as an angle, usually together with a wavelength. This angle describes the residual angle of the object space chief ray. Since the ideal target is 0°, we are usually talking about very small angles smaller than 0.1°. Exact 0° is usually never achieved: the angle depends on the wavelength of the light, but most lenses are designed for a whole range of wavelengths. Therefore, the best possible compromise must be found between the residual angle and the desired wavelength range for the use of the objective.

If we consider the angle of the main beam to the optical axis for three different wavelengths and the position of the main beam on the sensor for a telecentric 1X objective, the angle at the center of the image is 0°: Here the main beam coincides with the optical axis (**Fig. 3**). In the direction of the image corner, a monotonic function usually describes the main beam angle: the further away from the image center, the larger the angle. In the example, the angle at 5.5 mm – corresponding to a sensor with 11 mm diagonal or 2/3-inch format – reaches a value of about 0.1° for light of wavelength 486 nm. However, the function does not always have to be monotonic and can differ, especially for other wavelengths. For red light (656 nm), the angle at 5.5 mm is only about 0.015° – and the curve shows a change of sign. At about 4.4 mm image height, the angle is 0°.

It is therefore advisable to use a graph of this type instead of referring to a single value in a spec sheet. Furthermore, it is recommended to recalibrate an optical measuring system when working monochromatically and changing the wavelength of the light.

Summary

This article presents the applicational advantages as well as the functionality of object space telecentric lenses. Image space telecentric lenses can also offer benefits. These are less sensitive to the exact position and location of the sensor in the camera. In addition, the radiometric effect described in the $\cos^4$ law is avoided: the intensity of the light will decrease from the center away to the image edge with the factor $\cos^4$(CRA), where CRA stands for the image space chief ray angle. For a telecentric lens, this angle is 0°, so the factor equals 1. Provided that the lens does not have mechanical vignetting in conjunction with the sensor used, no apparent drop in relative illumination will therefore be observed. A final advantage of image space telecentrics kicks in when using precise optical filters installed between the lens and the camera. These filters are usually designed for an angle of incidence of 0°. The more one deviates from this angle, the more the filter response shifts to shorter wavelengths. The filter transmission would thus not be uniform over the sensor area, which is usually not acceptable for precise measurements in e. g. fluorescence or hyperspectral imaging.

For optical metrology, the factor of the lower sensitivity to the exact sensor position is usually most important. In order to achieve the best possible measurement results, it is recommended to use bi-telecentric lenses, which combine the advantages of both concepts.

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