Bilateral telecentricity -

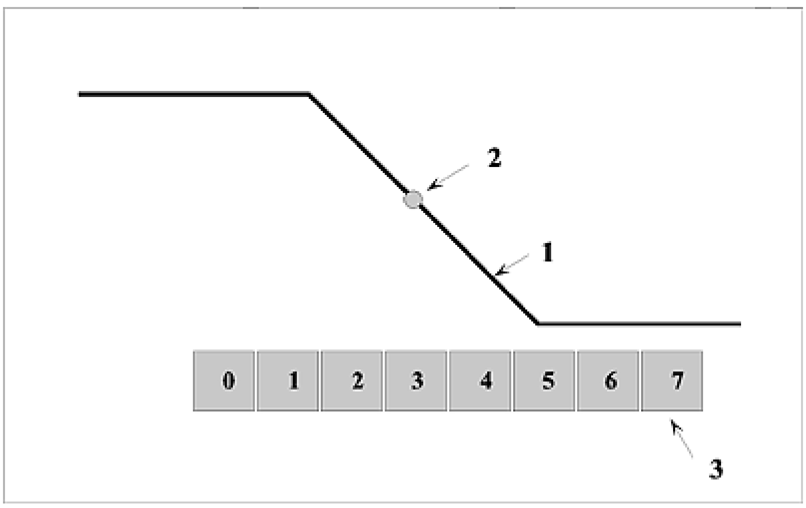
a precondition for high-precision optical metrology

Author : Dr. Rolf Wartmann, Bad Kreuznach

In the last few years, the techniques of non-contact optical measuring technology have experienced a tremendously rapid increase. This has come about, in the first place, because the use of electronic image processing has made it possible to automate whole chains of processes. In the wake of this development, the object-side telecentric lenses have become more and more widely accepted. Their ability to form an image independent of its distance, but always with the same size, is the basic precondition for a successful automatized measurement process. While object-sided telecentrics moved into the center of attention, the image side, i.e., the area between the lens and the camera, disappeared almost completely from view. At the same time, the organization of this side is just as important for highly exact measurement technology as that of the object side.

1. Basic principles of edge detection

Optical measurement technology is confronted by the problem of having to achieve high accuracy with relatively wide-surface sensors, which fall below the sensor dimensions by several multiples. As a rule, this problem is solved by blurring the edges of the test specimen across several pixels with the help of an fuzzy image. This technique thus makes possible the so-called sub-pixel edge detection, by which precision measurements of up to a tenth of the pixel size (in some cases, even less) are achieved. In Picture 1, the basic principle of edge detection is presented. Here the edge of an idealized test specimen is represented as defocused. It extends as a rising linear progression across several pixels (in this example, there are five).



Picture 1:
Edge depicted as defocused

1 - edge image,
2 - edge position to be detected
3 - pixel of the sensor

IAt the center of the edge function, where the energy level is at 50%, lies the edge position to be detected. The pixels numbered 1, 2, ..., j, lie within the edge image, and receive energies I_1, ...I_j. Let the pixels numbered 0 and j+1 be placed above and below the edge. Let the energy received be I_0 or I_{j+1}. The position of the edge b, measured as the distance from the beginning of the pixel having the number 1, has the value

$$b = a\left\{\frac{j}{2} + \frac{1}{j-1}\sum_{k=2}^{j}\frac{I_k - f_m}{I_{k-1} - I_k}\right\} \qquad (1)$$

whereas a represents the pixel size and fm is the energy level for 50 %. fm is calculated from.

$$f_m = \frac{I_0 + I_{j+1}}{2} \qquad (2)$$

This formula (1) is only one possibility for the detection of edges. There are several other formulas of equal value. Here, (1) stands as a representative for all edge detection formulas. Since the mathematical background is always similar, the statements made here about (1) apply to other edge detection algorithms as well.

With the help of edge detection, the position of the edge can be determined exactly, not only when the edge function is linear, but also that of all symmetrical edge progressions. The algorithm operates inaccurately, however, when the edge function is asymmetrical. In particular, the shift of the sensor relative to the edge in this case effects a displacement of the edge position.

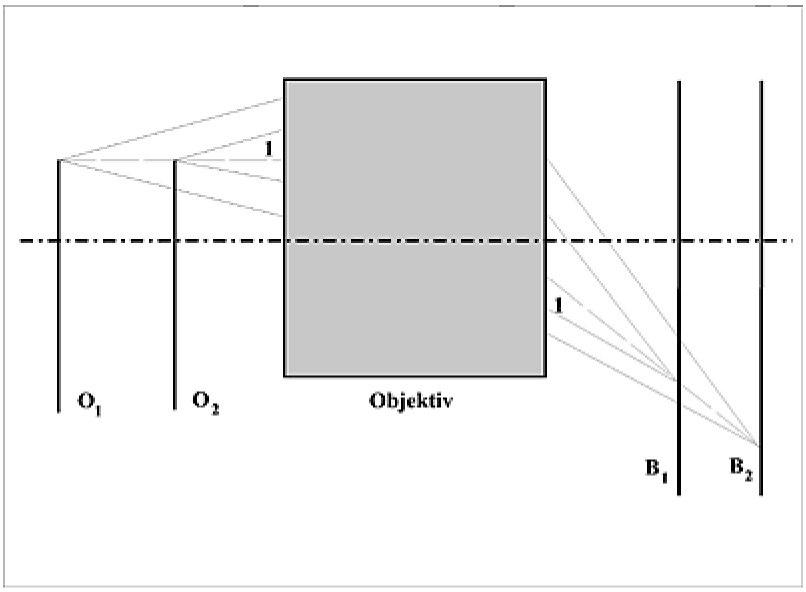
2. Change of symmetry of the edge image when defocussing

With automatized non-contact measurement, it is impossible to measure the test specimens again and again exactly from the same position. In the last analysis, it is this condition that has led to the development of object-side telecentric lenses. On the image side, the inexact positioning of the test specimen, however, also has an effect on the accuracy of measurement. This effect is represented in Picture 2.

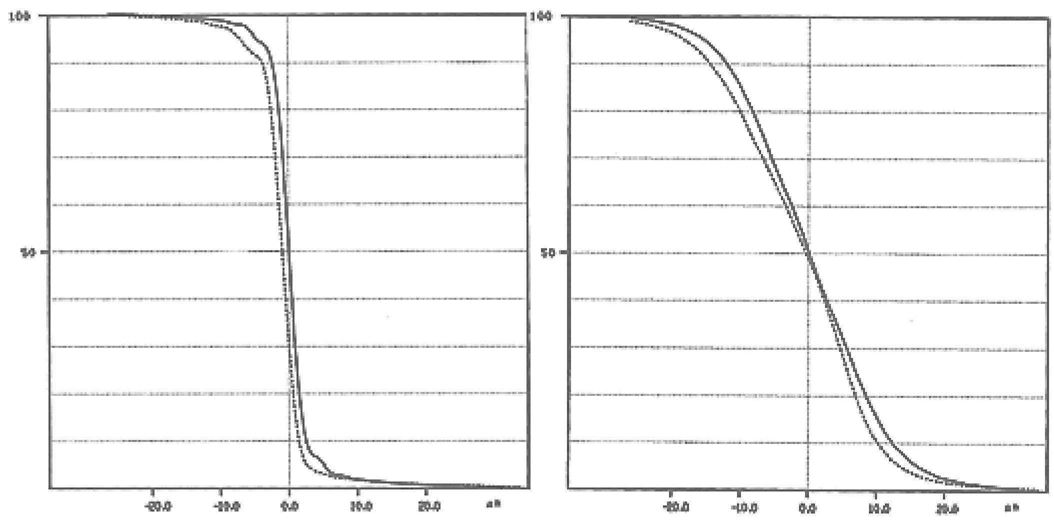
Picture 2:
Bilaterally telecentric lens

O_1, O_2 - Positions of the test sample,
1 - Principal ray

B_1 - Sensor position,
B_2 - Image plane for the test sample's position O_2



The point of departure is the positions of two test specimens O_1 and O_2. From position O_1, the test specimen is sharply depicted on sensor plane B_1. If the test specimen is in O_2, it is sharply depicted according to B_2. In B_1, the test specimen presents a fuzzy image, which from the point of view of form, however, exhibits the same size as the representation from O_1. This consistency of size derives from the fact that the principal ray is projected **telecentrically** on the object side, i.e., parallel to the optical axis. The reason that there is a fuzzy image in B_1, however, is because it is asymmetrical. It can be seen very clearly in Picture 2 that the beam of light, which in B_1 produces the image of O_2, is asymmetrical. The upper part of the beam illuminates a larger area of B_1 than the lower part. In actual situations, the effects of this phenomenon can be observed in connection with defocusing of some tenths of a millimeter.

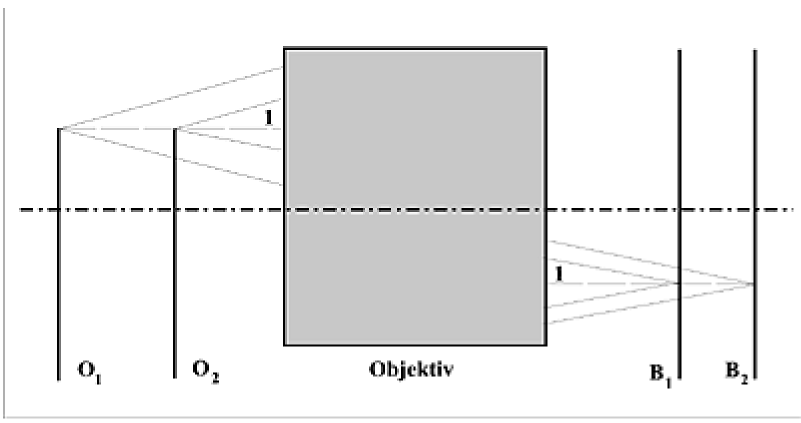


Picture 3: Edge images of a lens without image-side telecentrics
exactly focused and defocused by -0.3 mm � � � � radial --------- tangential

Picture 3 shows the edge image function for a lens which, when correctly focused, shows no asymmetry of any kind (Graph 1). If it is defocused by -0.3 mm, the tangential edge image becomes asymmetrical. The same result can also be observed with a defocusing of +0.3 mm. In addition to that, a drift of the edge position in tangential direction can be noted. If both results are included in this example, then the possibility of a measure of uncertainty of up to +/- 4 m in the detection of the tangential edge must be reckoned with. If one considers that a detection accuracy of +/- 1m is quite possible and, given optimal illumination, can even be exceeded, then this degree of uncertainty constitutes a significant reduction of the accuracy of measurement. Similar inaccuracies occur even if the sensor is not level or does not stand vertical to the optical axis.

3. Advantages of bilateral telecentrics

The effects of changing the symmetry of the edge image in connection with defocusing, as described above, bring about a noticeable loss of measurement accuracy. These can be avoided if the measurement lens used is designed for telecentrical use, not only on the object side, but also on the image side. Picture 4 shows the basic principles of imaging with such a lens.



Picture 4:
Bilaterally telecentric lens

O_1O_2 - Positions of the test sample,
1 - Principal ray

B_1 - Sensor position,
B_2 - Image plane for position of the test sample O_2

In this instance, the imaging situation corresponds to that of Diagram 2, i.e., O_1 is sharply depicted in sensor plane B_1, but from O_2 a fuzzy image occurs in B_1. The significant difference in Picture 2 consists in its **image-side telecentrics**, the direction of principal ray 1 in the image area being parallel to the axis. Because of this telecentricity in the image area, the image is washed out symmetrically from O_2 in B_1, because the split field of B_1 with the light beam represented is circular. As a result, the edge image remains symmetrical, despite defocusing, and the edge can be detected exactly. In the last analysis, when bilateral telecentric lenses are used, the degree of accuracy of detection theoretically possible can be attained if the conditions of illumination and the structure of the edges are optimal.

4. Bilaterally telecentric measurement lenses from Schneider Kreuznach

Because of the constantly increasing requirements for the accuracy of non-contact measurement systems, we have decided to market a series of bilaterally telecentric measurement lenses. The series comprises **five** lenses with the **image scales** of 1:1 to 1:5. In addition to the distinguishing feature of bilateral telecentrics, these lenses have the following additional features:

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- The lens speed was significantly increased in comparison to those lenses which are currently available on the market. The numerical aperture is 0.14 or 0.13.
- The lenses are focusable on the image side in a range of � 3 mm. For this reason, the working distance can be variously adjusted on the object side. The limits for this are, to be sure, dependent on the image scale. The metering ranges for the five lenses with the image scales 1:1, 1:2, 1:3, 1:4, and 1:5 are 6 mm, 24 mm, 54 mm, 96 mm, and 150 mm. The image scale remains constant when refocusing.
- The lenses manifest very little distortion. With suitable calibration, distortion can easily be eliminated.

5. Summary

When image-side telecentrics are absent in measurement lenses, asymmetric or drifting edge images arise when defocusing. This leads to inexact detection of edges, with the result that the degree of accuracy which is theoretically possible is clearly not attained. Bilaterally telecentric lenses do not exhibit these flaws, and thus make it possible to come close to the theoretically possible degree of accuracy.

FON : +49 671 601-0 .... **FAX** : +49 671 601-286 .... **E-mail** : industrie@schneiderkreuznach.com