TUTORIAL #1

Telecentric Lenses: basic information and working principles

On line dimensional control is one of the most challenging and difficult applications of vision systems. On the other hand, besides image processing problems, several factors limit measurement accuracy and repeatability:

a) magnification change with object position change
b) distortion
c) perspective errors
d) image resolution loss along the field depth of non-bitelecentric lenses
e) edge position uncertainty due to object border lighting geometry

Telecentric lenses allow the impact of all these problems to be strongly reduced or even cancelled, for this reason being a must for all those developing measurement applications.

Below we try to explain how telecentric lenses work and why the above effects are reduced or eliminated.

A - No magnification change with object position

In several situations the piece being inspected cannot be placed at a precisely determined distance from the lens: this is particularly true for on line applications where the pieces can be put in vibration or its thickness (therefore the object surface position) can be variable.
Common lenses give a different magnification at different conjugates: as a consequence the image of the same object placed in different positions changes almost proportionally with object to lens distance, as everybody can easily experience with his vision system.

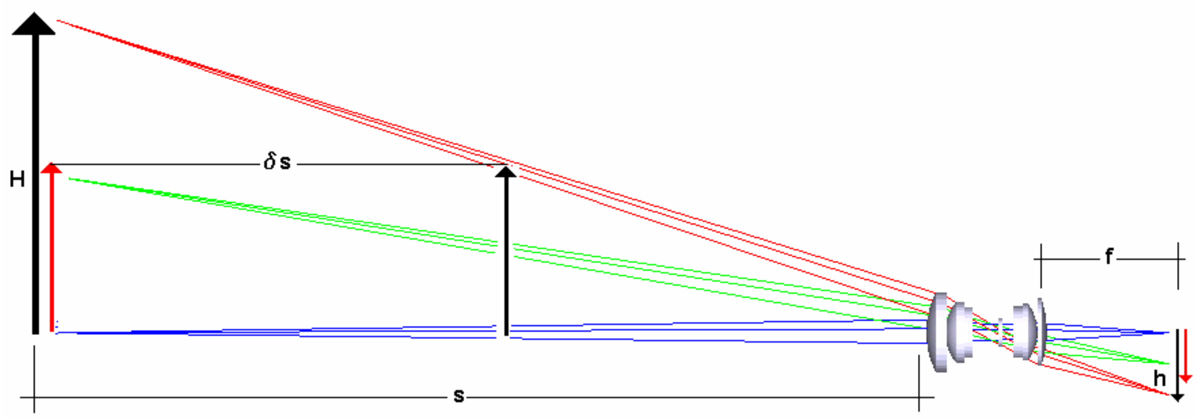


Fig. 1: standard lenses generate images of different size if a same object changes its distance from the lens. On the other hand objects of different size can be viewed as if they had the same dimension, if they subtend the same viewing angle.

With telecentric lenses the image size remains almost unchanged when the object distance changes, provided the object to be inspected stays within the given field depth/telecentric range.

This is due to the particular path of the rays within the optical system: the objective accepts form the object to be imaged only cones of rays whose barycentric ray (or *principal ray*) is parallel to the opto-mechanical main axis (for this reason the front lens diameter is at least as large as the object field diagonal). This is made possible because the stop aperture is placed at the focus of the front optical group: this causes the entrance pupil to be seen, by the rays coming into the optics, as if it would be placed at the infinity. For this reason these lenses are called telecentric, because the pupil aperture (the *center* of the optics), is virtually placed at infinity (*tele-*, far, from the Greek).

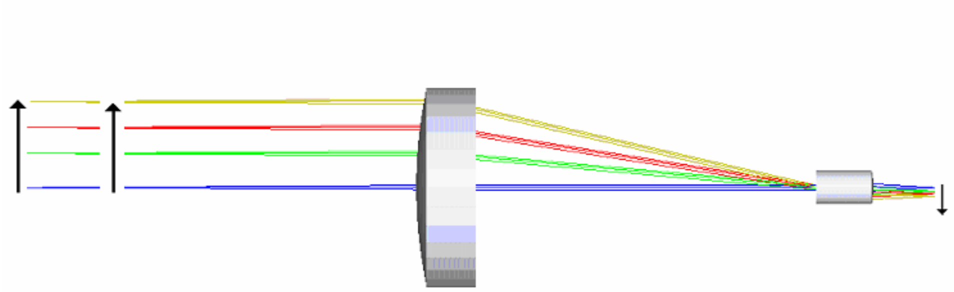


Fig. 2: in a telecentric system rays get into the optics only with an almost parallel-to-the-axis path.

Just to get the feeling of the difference between the two objective kinds, let suppose, for instance, a common lens of focal length $f = 12\ mm$, interfaced to a *1/3"* detector, looking at an object of height $H = 20\ mm$, at a distance $s = 200\ mm$.

If the object is moved, from its original position, of $\delta s = 1mm$, the change of its dimension appear to be about:

$$\Delta H = (\delta s/s) \cdot H = (1/200) \cdot 20\ mm = 0{,}1\ mm$$

In a telecentric lens the magnification change is determined by the telecentric slope:

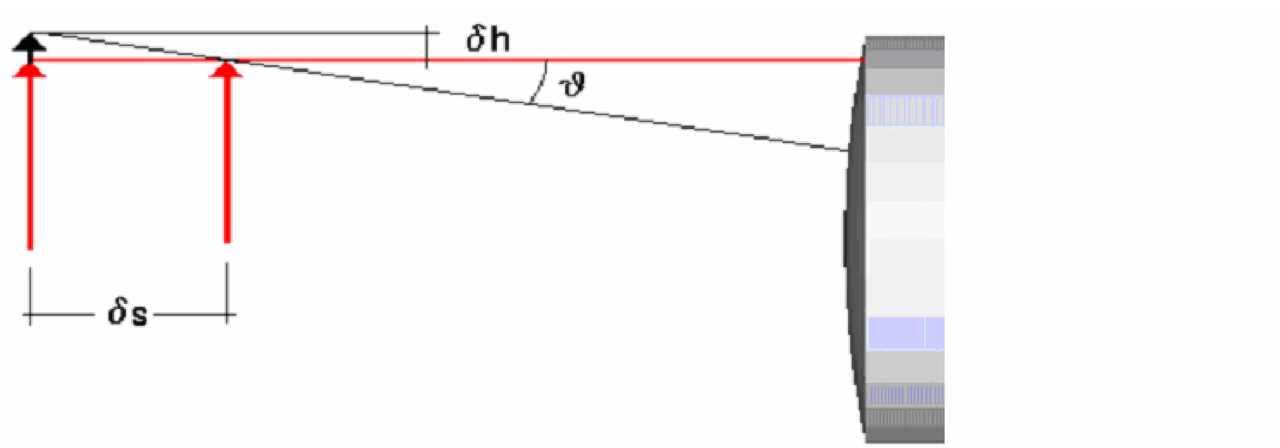


Fig. 3: the telecentric slope determines the magnification change

Good telecentric lenses show an *effective* telecentric slope of about *0,1°* (*0,0017 rad*) as in the case of Opto Engineering's lenses; this means that the object dimension appear to change of only *0,0017 mm* for each displacement *δs* of *1 mm*. Thus, with telecentric lenses the magnification error is *1/10* to *1/100* in comparison with common lenses.

B – Distortion control

Distortion is one of the worst problems limiting measurement precision, because all lenses suffer at least of a minimum distortion, and often even a single pixel of difference between the real image and the expected image is critical.

Distortion is simply defined as the percentage difference between the distance from the image center of real image point and the distance that would be measured in complete absence of distortion.

For instance, if the corner of the image of a square has a distance from the image center of 198 pixels, but a distance of 200 pixels would be expected in absence of distortion, the distortion, at that point, is

$$Dist = (198-200)/200 = -2/200 = 1\%$$

Positive distortion is also called "pincushion" distortion, negative distortion is called "barrel" distortion: note that the distortion depends on the radial position and can even change of sign.

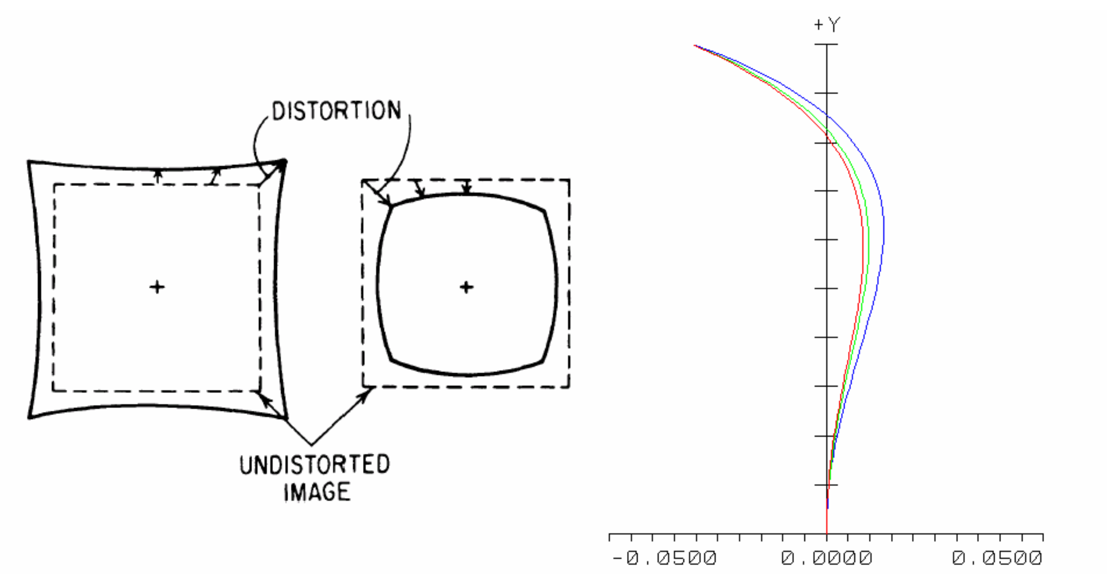


Fig. 4: Pincushion and barrel distortion. On the right the graph of the distortion correction of a telecentric lens of Opto Engineering

Common optics present distortion values ranging from some percent to some tenth percent, making precise measurement really difficult, also because the correction of the distortion is complicated by the absence of telecentricity. The presence of distortion is due to the fact that the human eye can easily compensate a distortion of 1, 2% and, as most of the optics used in machine vision has been developed for video-surveillance or photography, this is enough.
In some cases, like in fish eye lenses or web-cam style lenses, distortion is expressly introduced to help the lens to work on large angles and to guarantee an eve illumination of the detector.

Telecentric lenses normally show a very low distortion degree, in the range of 0,1%: this means that the maximum error due to distortion should be less than a pixel of a high-resolution camera (0,6 pixels on the semi-diagonal of a VGA).

Few people know that the distortion depends upon the distance of the object, not only upon the optics itself. For this reason it is very important that the nominal working distance be maintained and no focusing optical groups be present in the lens.

In any case, in many situations distortion has to be calibrated: a known pattern must be placed at the center of the field depth, the distortion must be measured in several image points and some algorithm must interpret the grabbed frame and to transform it into a distortion free image. To avoid non-axially symmetric distortion care has to be taken to provide a fine perpendicular alignment of the optics and the object to be inspected.

C- Perspective errors limitation

When common optics are used to image 3D objects, as was said above, far objects have smaller images than close objects. As a consequence, when an object like, for instance, a cylindrical cavity is imaged, the top and the bottom circular edges seem to be concentric even if the two circles are perfectly identical.
On the contrary by means of a telecentric lens, the bottom edge disappears because the top standing circular edge covers it.

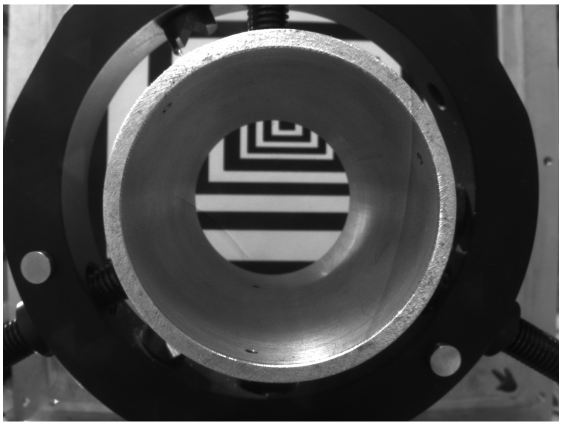


Fig. 5: Perspective error due to common optics (left image) and perspective error absence (right image) with a telecentric lens.

This effect is due to the specific path of the rays: in the case of common optics the geometric information "parallel" to the main optical axis shows a component on the detector plane direction, while in a telecentric lens this perpendicular component is not present at all.

You can think as if common lenses would build a correspondence between the 3-dimensional object space and the 2-dimensional detector (image) space: in the case of a telecentric lens the third dimension in object space is left out.

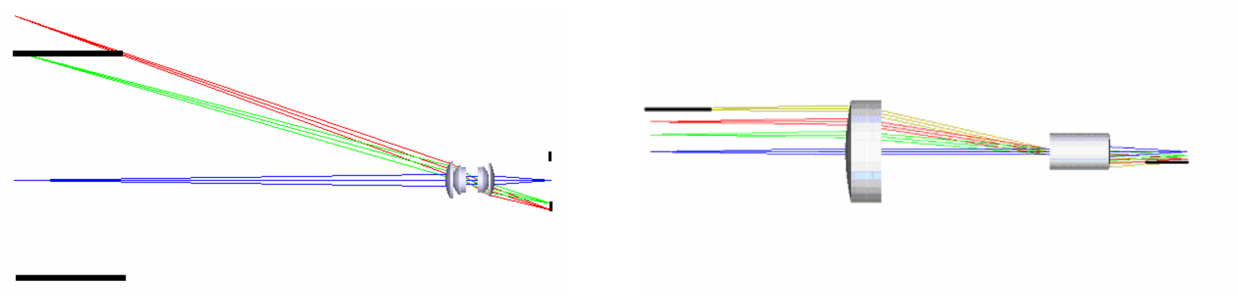


Fig. 6: Common optics (left) project longitudinal geometrical information onto the detector, while telecentric lenses

D- Good image resolution maintenance along the field depth

Filed depth basically depends upon the optics F-number: the largest the f-number (that is the smaller the optics aperture) the larger the field depth, with a quasi-linear dependence. This happens because field depth is the maximum object position departure accepted from the *best focus* situation. Behind this limit the image resolution isn't any more accepted, because the rays coming from an object point don't strike the detector surface in a sufficiently small "spot", more pixel are interested by the same object information (blur) and the focusing becomes bad.

Closing the lens diaphragm, that is raising the f-number - that simply is the ratio between the lens focal length and its apparent pupil aperture – diminishes rays divergence; the rays spread is consequently lower, allowing a smaller spot size onto the detector.

Common optics and normal telecentric lenses tend to have a worse behavior because the ray cones have different inclinations depending upon the field position. As a consequence of this, the spot generated by the intercept between the ray cone and the detector plane has a different shape and dimension at the image center and at the image borders (becomes elliptic and larger). In addition the spot barycentric point moves back and forth with image plane position. ***For this reason non bi-telecentric lenses have a poor field depth and a poor telecentricity!!!***

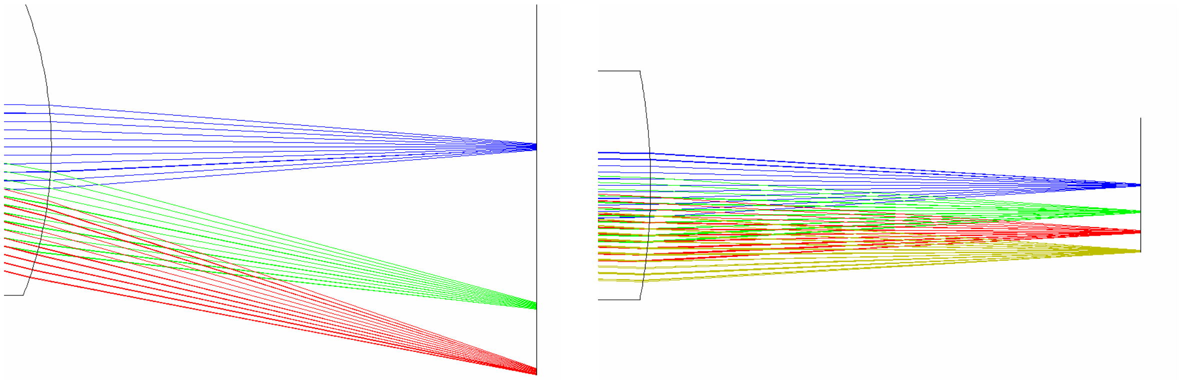


Fig. 7: In a bi-telecentric lens (right) the ray cones intercept the image sensor in a way independent on the field position, in a non image space telecentric lens (left) this doesn't happen.

E - Edge position certain determination and border effects limitation

Very often back lighting the subject makes difficult to determine the exact position of the object edge. This can happen because the signal of the bright pixels of the background tends to be overlapped to that of the dark pixels of the object edges, but if the object is highly 3D, another effect can strongly effect the measurement precision.

As shown in figure 8, rays coming from the peripheral zones of the object, being close to the object edges can be reflected by the object (almost any material approach a mirror if the incidence angle is large) and can be interpreted as rays directly coming from the back of the object. This means that some marginal slices of the object can disappear making the measurement really imprecise and unstable.

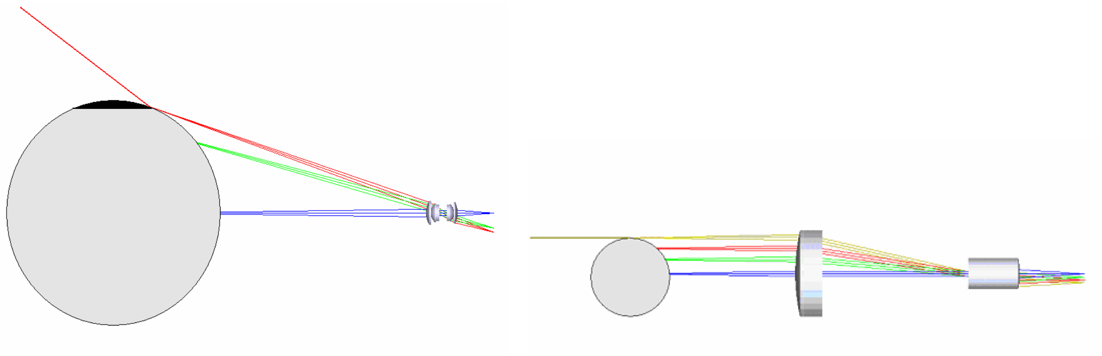


Fig. 8: Border effects in a common imaging lens are strongly reduced by means of a telecentric lens

This effect can be efficiently limited if a telecentric lens is adopted, because, if the f-number is not to "open", the only rays that can be reflected by the object surface and come into the optics are those parallel or almost parallel to the optical main axis (that are, thus effected by really very small deflections), that doesn't compromise too much the measurement.

To completely avoid this kind of problem Opto Engineering produces telecentric illuminators to be interfaced to telecentric lenses with the same aperture and full object field compatibility. In this way ALL the light coming out from the illuminator goes onto the detector, allowing extremely high signal to noise performances and incredibly low exposure time. On the other hand, the only rays coming into the imaging lens are those that are expected to and no border problems occur

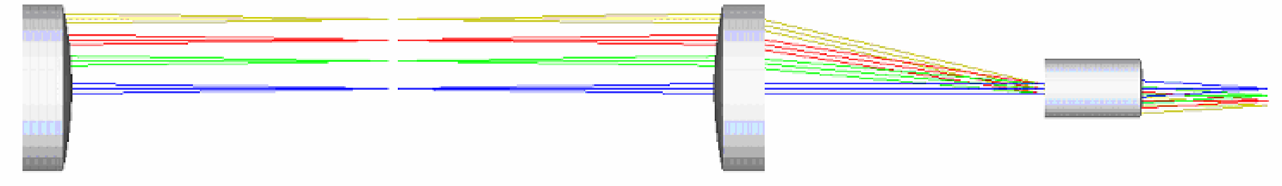
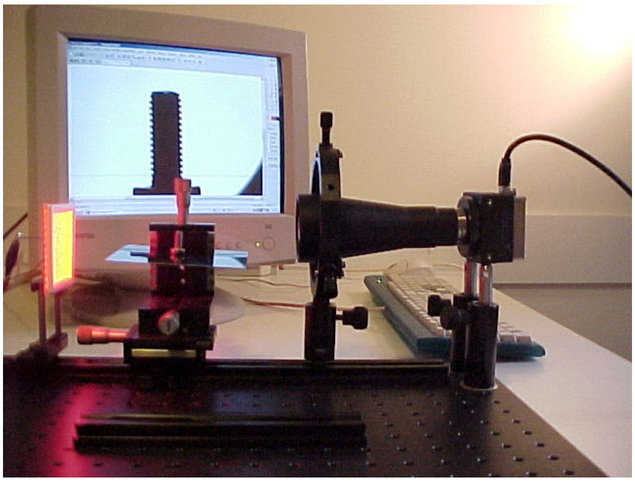


Fig. 9: Collimated or telecentric illumination projects into the imaging telecentric lens only the rays expected to.



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