Optical inspection of solids of revolution by means of non-telecentric optics

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Abstract. The paper dwells upon automated inspection of solids of revolution on machines. It demonstrates how digital cameras with non-telecentric lenses generate the cross-section image. The paper presents an evaluation of error arising from using projection with non-telecentric (entocentric) optics for inspection. The analysis implies lenses with a focal length of 7, 12, or 25 mm. The obtained analytical dependencies of perspective error are used to adjust the measurements. Simulation confirms that errors can be compensated to values within the calibration error.

1. Introduction
Despite all the progress that has been achieved in instrumentation, engineers are yet to implement real-time monitoring of products in machining to generate adaptive CNC machine control algorithms based on direct quality indicators.

Automated control of mechanical engineering products is mostly based on the coordinate method using contact gauge heads. When measuring real-world elements of deviant shape, the number of measuring points may vary from 3 for straight lines to 50 for circles. The method is suboptimal: locating the measured points one by one takes too long, effectively preventing any use of this method for real-time monitoring in machining. Given how many such elements can be present in a single mechanical engineering product, time to inspect a single product may be as long as tens of minutes.

Optical instrumentation has long found use in mechanical engineering, mostly for manual control. However, the advancements of optoelectronics gave rise to automated systems such as the batch monitoring system or the instrumentation from ViciVision. The systems are based on analyzing 2D shadow images of the symmetry plane and use telecentric optical systems with collimatory lighting. Measurements usually employ backlight. The main advantage of telecentric optics is the constant magnification across the entire operating range, which prevents perspective distortions for extended objects. At the same time, telecentric systems are not without weaknesses: high-quality wide-aperture optics is costly, the field of view is limited by the size of lens (up to 250 mm), and the optics layout has its limitations, too, due to the use of backlight.

2. Statement of Problem
Non-telecentric optical systems are not common in monitoring extended objects due to their variable magnification and perspective image distortions. The first disadvantage can be compensated if the location of the inspected object with respect to the digital imaging camera is known; this compensation will use calibration against test objects of known properties. Calibration establishes a mathematical
dependency between the inspected object image and pre-image, which takes into account the distortions of a specific optical section. Algorithms compensating the errors of passive optoelectronic systems make linear sizing accurate enough to be on par with 5 MP digital cameras. However, when inspecting non-stationary or extended objects by their 2D images (which includes solids of revolution as well), the occurring projection distortions must be taken into account. Let us consider imaging a solid of revolution by an ideal optical system. Figure 1 shows how image is generated with non-telecentric optics. To visualize the size, ratios are shown for a case of 7 mm lens with a 1/3” photosensitive matrix.

Figure 1 shows that the pre-image of the solid of revolution D has a visible size d (1):

\[ d = D \cdot \sqrt{1 - \left(\frac{D/2}{L-f}\right)^2} \]  

(1)

where D is the object diameter, L is the distance to the object, f is the focal length.

The visible image is smaller than the object itself, and becomes even smaller at shorter focal length. The image is thereby displaced along the optical axis by l (2):

\[ l = \frac{D^2}{4(L-f)}. \]  

(2)

As can be seen in Figure 1, the section image on the symmetry axis D’ is smaller than the visible image d’. This becomes apparent as auxiliary beams pass through the focus. This results in errors when sizing the surfaces of revolution.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Imaging a solid of revolution by non-telecentric optics}
\end{figure}

3. Research Results
Let us evaluate the perspective error based on the laws of geometrical optics while neglecting the distortions of the transmission path. Then the digital-camera matrix image d’ of the SoR section can be defined by the dependency (3):

\[ d' = d \cdot \left(\frac{f}{L-l-f}\right). \]  

(3)
Using simple calibration against a test object placed perpendicularly to the optical axis and aligned with the symmetry axis of the solid of revolution, the following formula will return the relative error of finding its size (4):

\[
\delta D = \frac{d' \cdot V - D}{D}
\]

where \( V \) is the linear magnification.

The obtained dependency has been used to plot the curve in Figure 2, which shows the error of measuring the dimensions of a notched body with \( D \) notches measuring 20, 40, 60, 80, or 100 mm, using a digital camera with \( f = 7, 12, \) or 25 mm; the inspected object is placed at a distance \( L = 198, 340, \) or 708 mm, respectively.

![Figure 2. Sizing error](image1.png)

This dependency can be used to correct the perspective errors, which will drastically reduce the sizing error. Figure 3 shows a simulation of correcting the error in case of an ideal optical system used to measure the size of elements of revolution.

![Figure 3. Corrected sizing error](image2.png)

Evaluate the effect of SoR symmetry axis displacement against the optical axis. Figure 4 shows the imaging diagram.
Figure 4. Diagram of imaging the surface of revolution as the optical axis is displaced with respect to the symmetry axis

When the shaft axis is displaced by $y$ with respect to the symmetry axis of the solid of revolution, the image rotates by the angle $\alpha$ (5):

$$\alpha = \tan^{-1}\left(\frac{y}{L - l}\right).$$  \hfill (5)

The auxiliary-beam path through the focal point $F$ remains unaltered; accordingly, the image size will change by (6):

$$\Delta = D \cdot \cos \alpha.$$  \hfill (6)

When calibrating a system, one must seek to make the test object perpendicular to the optical axis of the lens, as displacing it will cause a projection error that conforms to the formula (7):

$$\Delta = D \cdot \cos \beta$$  \hfill (7)

where $\beta$ is the test object tilt angle.

Thus, the considered factors will cause a projection error.

If the required measurement accuracy is 0.05%, test object deviation of up to $1^\circ$ is acceptable.

4. Conclusions

For short-focus lenses, the error arising from projection distortions when sizing a surface of revolution is considerable; it may reach up to 2% even within 80% of the field of view. For long-focus lenses, the error is also substantial, as it exceeds the resolution of a 0.3 MPX camera.

Simulation shows the error can be near totally compensated for 25 mm; meanwhile, compensation is practically sufficient for 12 mm lenses. Short-focus lenses are rarely used in instrumentation; 0.12% perspective error is comparable to the attainable calibration of such lenses.

If the required measurement accuracy is 0.05%, test object deviation of up to $1^\circ$ are acceptable.

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