Measuring the diameter of a cylinder with automatic calibration

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Abstract. The work aims at developing a method for measuring the diameter of cylindrical objects, eliminating the need for calibration and verification of the measurement system during operation. The system for measuring the diameter of cylindrical objects contains a photodetector and a light source located on opposite sides of the measured object to implement the shadow method. The proposed method is based on the measurement of two reference cylinders located in the measuring area for automatic calibration of the system at each measurement. It is shown that the proposed method provides stable reliable measurements with an error of less than 2 μm for the diameter of the measured cylindrical objects of up to 10 mm.

1. Introduction
Currently, various techniques are widely used for high-accuracy non-contact measurement of the cylinder diameter. The most common methods are based on forward and backward scattering of light [1–3].

The best values of the diameter measurement accuracy are provided by shadow and diffraction methods of measurements on forward scattering of light [4–6]. Such methods allow achieving an error at 0.01% of the range. Despite the high measurement accuracy and high reliability of existing technical solutions, measuring systems require periodic adjustment. This is due to thermal drifts of electrical components, instability in optical channels, or contamination of optical elements. To solve this problem, as a rule, the user performs a periodic test of the measuring system operation, for example, using a reference cylinder with a known diameter. This test, on the one hand, allows checking serviceability or malfunction of the measuring system, and on the other hand, enables meter adjustment operation to ensure the correctness of the measurement results.

This work aims at developing a method for measuring the diameter of cylindrical objects, eliminating the need for a calibration procedure and verification of the measurement system during operation.
2. Method description

The system for measuring the diameter of cylindrical objects contains a photodetector and a light source located on opposite sides of the measured object (Fig. 1). The photodetector is equipped with telecentric optics to reduce the influence of the position of the measured object on the "visible" geometric size of the cylinder. The light source and the photodetector operate in a synchronous mode, which serves to measure the moving objects. To achieve this goal, a solution is proposed based on the use of two reference cylinders in the measurement zone. The diameter of a cylindrical object is measured as follows. The photodetector takes an image of the cylinder shadow in the measurement area. Using the gradient search, we find the boundaries of the cylinder in the image and calculate the average diameter $P$ in pixels. Gradient search contains next steps: image smoothing, differentiate in vertical direction and search local extremum.

The dependence of the object's diameter on the image size $P$ is described by the formula (1):

$$D = K \times P + N,$$

where $D$ is the diameter of the measured object, $P$ is the size in pixels (measured by the camera), $K$ is the scale factor, and $N$ is the linear correction factor. The scale factor and the linear correction factor are determined by formulas (2) and (3), using the measurement of two calibration cylinders of known diameters $R_1$, $R_2$:

$$K = (R_1 - R_2)/(P_1 - P_2)$$

$$N = (R_1 \times P_2 - R_2 \times P_1)/(R_2 - R_1)$$

The measurement algorithm is as follows:

1. Arrays of coordinates $P_1(x)$ and $P_2(x)$, corresponding to the coordinates of the upper and lower boundaries of the cylindrical object, depending on the horizontal coordinate, are found on the obtained image of the object using the gradient boundary search algorithm.
2. By the jump of the coordinate value, the left and right boundaries of the cylindrical object are determined.
3. The arrays $P_1(x)$ and $P_2(x)$ are filtered using the criterion for excluding sharp outliers.
4. From the angle of inclination of the dependence of the function $P_1(x)$ and $P_2(x)$, the angle of rotation of the object relative to the image horizon is found.
5. The dependence of the apparent diameter of the cylinder on its horizontal coordinate $P(x)$ and the height of the cylinder in pixels is obtained.
6. We obtain the dependence of the object diameter in millimeters on the horizontal coordinate in the image and the object height in millimeters using the scale factor and the correction factor.
Figure 2. Image in the frame of the measuring system.

In the proposed method, the dimensions of the calibration cylinders may not cover the entire measurement range. The use of a large calibration cylinder will lead to change scale of the entire image, increase the number of microns per pixel and, as a result, increase the measurement error. In this regard, the dimensions of the calibration cylinders were selected based on the minimum size that can be used on the images of the measured cylinders.

As a result, the proposed method for measuring the cylinder diameter with automatic calibration provides automatic recalculation of the scale and linear correction factors. This approach ensures the operation of the measuring system without carrying out the adjustment procedure and verification during operation.

3. Experimental results

The tests of the created experimental model of the system for measuring the diameters of cylindrical objects with a diameter of 1-10 mm are carried out. Calibration cylinders with diameters $R_1 = 1$ mm, $R_2 = 2$ mm are used. A photodetector DMK 33GX264 with a telecentric lens TC23024 is used. Monochrome LED emitters with a total power of 20 W and a radiation wavelength of 450 nm are used as a light source. To exclude parasitic illumination, an optical narrow-band filter at 450 nm and synchronous pulsed illumination are used on the photodetector.

Figure 3. Experimental setup for measuring the diameter of cylindrical objects.
1 – light source, 2 – bracket for measured objects, 3 – photodetector.
In the experiment, 36 samples of cylindrical objects with different diameters in the range of 7.8 - 8.3 mm were measured. Each cylinder was measured 3 times to check the reproducibility of the readings. Fig. 4 shows the measurement results.

![Figure 4](image)

**Figure 4.** Measurement results of sample cylinders.
N – measurement number, D – measured diameter.

Fig. 5 shows the dependence of the measured diameter of a cylindrical object on its real value. The actual size of the cylinder is measured with a mechanical contact micrometer by taking 10 successive measurements and calculating the average value. The graph demonstrates the reliability of the measurement results.

![Figure 5](image)

**Figure 5.** Dependence of the measured value of the diameter D of a cylindrical object on its real value Do.
Based on the data obtained, the measurement error has been estimated. The root-mean-square deviation of the measured diameter is found not to exceed 1.5 μm.

Conclusions
The paper proposes a method for measuring the diameter of cylindrical objects with automatic calibration. The method is based on the measurement of two reference cylinders located in the measurement area to automatically calibrate the measurement system with each measurement. Experimental studies of the proposed method have been carried out. It is shown that the proposed measurement method provides stable reliable measurements with an error of less than 2 μm for the diameter of the measured cylindrical objects of up to 10 mm. As a result, the application of the proposed approach completely eliminates the need for verification and high-precision adjustment of an optical precision system for measuring the diameters of cylindrical objects in an industrial environment.

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