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TWO-DIMENSIONAL POSITION MEASUREMENT OF OBJECTS WITH CIRCULAR CROSS-SECTION USING SINGLE LINEAR CCD SENSOR

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Abstract: This paper describes a novel method of two-dimensional position measurement of objects with circular cross-section. The proposed method employs a single linear CCD sensor and two point light sources. Using this simple measuring set-up the described method achieves typical linearity deviations below 4.5 µm in the direction along the senor and 22 µm in the direction perpendicular to the sensor.

Keywords: 2D position measurement, linear CCD sensor, point light sources.

1. INTRODUCTION

Two-dimensional position measurement of e.g. workpieces or machine tools represents a complex task. Conventional solutions of this problem include the application of standard CCD cameras equipped with telecentric lens (standard lens are not applicable due to the dependence of the magnification on the distance between the measured object and the camera) or the usage of two sensors based on the projection of the object's shadow [1] as shown in Fig. 1.

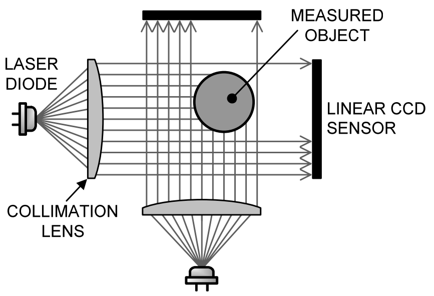

Fig. 1. Position measurement of an object with circular cross-section

Total dimensions and cost of the telecentric lens together with relatively small measuring area (given by the telecentric region and by the dimension of the CCD chip) may represent a major issue in case of the first solution. The application of the latter solution (Fig. 1) is complicated by the two sensors and two illuminators that are required.

The novel solution described in this paper enables to measure the two-dimensional position using a much simpler measuring configuration. This so-called *triangulation method* of position measurement requires only one linear CCD sensor and a proper illuminator.

2. TRIANGULATION METHOD OF POSITION MEASUREMENT

The triangulation method is based on measurement using the shadow projected on an imaging sensor (such as CCD or CMOS sensor) without lens. Contrary to conventional methods which apply a source of a collimated light beam (Fig. 1), this novel method employs point light sources. Point light sources enable to simplify the measuring set-up because they use no optical elements such as collimation lens. Furthermore, thanks to the divergence of the light beam emitted by such light source, they enable to measure the object's position in two axes even when using only a single linear imaging sensor (e.g. linear CCD sensor).

2.1. Principle of the method

In order to determine the measured object's position in the direction of axes *x* and *y*, two point light sources are required (Fig. 2). The measurement using the triangulation method consists of two steps: in each step only one of the light sources is on and the other is off.

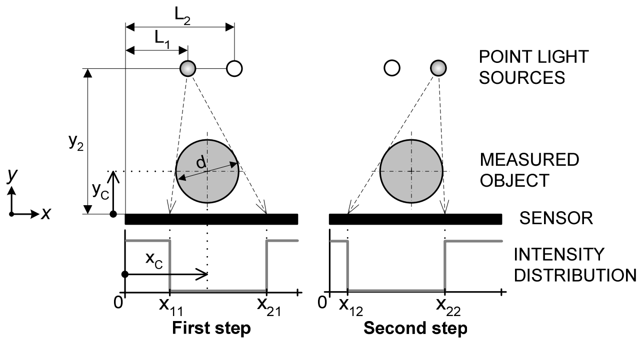

Fig. 2. Position measurement of an object with circular cross-section using the triangulation method

The position x_C of the measured object in the direction of axis *x* (along the sensor) is then calculated using (1). The equation employs the positions of the edges x_{11} and x_{12} in the intensity distribution (i.e. positions of the boundaries between light and shadow), the object's diameter *d* and the parameters of the measuring set-up (the positions of the point light sources: L_1, L_2 and y_2). Similarly, the position y_C in the direction of axis *y* (in the direction perpendicular to the sensor) is determined using (2).

$$x_C = \frac{L_2 x_{11} - L_1 x_{12}}{L_2 - L_1 + x_{11} - x_{12}} + d\,\frac{(L_2 - x_{12})\sqrt{(L_1 - x_{11})^2 + y_2^2} - (L_1 - x_{11})\sqrt{(L_2 - x_{12})^2 + y_2^2}}{2(L_2 - L_1 + x_{11} - x_{12})\,y_2} \qquad (1)$$

$$y_C = y_2\,\frac{x_{11} - x_{12}}{L_2 - L_1 + x_{11} - x_{12}} + d\,\frac{\sqrt{(L_1 - x_{11})^2 + y_2^2} - \sqrt{(L_2 - x_{12})^2 + y_2^2}}{2(L_2 - L_1 + x_{11} - x_{12})} \qquad (2)$$

$$d = \frac{2\,y_2\,(x_{21} - x_{11})(L_2 - L_1)}{(L_2 - L_1 + x_{21} - x_{12})\sqrt{(L_1 - x_{11})^2 + y_2^2} + (L_2 - L_1 + x_{11} - x_{12})\sqrt{(L_1 - x_{21})^2 + y_2^2} - (x_{21} - x_{11})\sqrt{(L_2 - x_{12})^2 + y_2^2}} \qquad (3)$$

Both equations (1) and (2) require the knowledge of the measured object's diameter d. In case the diameter d is not known, the triangulation method enables to calculate it using equation (3) that employs similar parameters as the previous two equations [2].

2.2. Measuring area

When using point light sources to illuminate the measured object, attention has to be paid to the shape and dimension of the measuring area. In case of the conventional solution which applies a source of a collimated light beam (Fig. 3a), the measuring area (i.e. the area in which the measured object has to be placed in order to measure its position) is rectangular in shape and its width is equal to the beam's width. When using point light sources (Fig. 3b) the measuring area is triangular and its dimensions depend on several parameters of the measuring set-up such as the distance between the light sources ($L_2 - L_1$), the distance between the sensor and the light sources (y_2) and the distance between the measured object and the sensor (y_1).

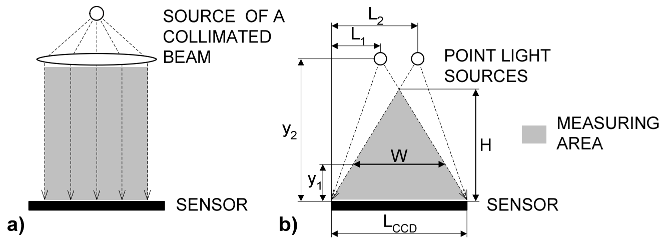

Fig. 3. Measuring area.

The width W (in distance y_1 from the sensor) and the height H of the measuring area can be calculated using the following formulas:

$$W = L_{\mathrm{CCD}}\left(1 - \frac{y_1}{y_2}\right) - (L_2 - L_1)\frac{y_1}{y_2} \qquad (4)$$

$$H = \frac{y_2 L_{\mathrm{CCD}}}{L_{\mathrm{CCD}} + L_2 - L_1} \qquad (5)$$

From Fig. 3 it follows that in case of the proposed method the measuring area is generally smaller compared to the area of the conventional method.

3. IMPLEMENTATION OF THE TRIANGULATION METHOD

In this paragraph, several issues related to the implementation of the proposed method are discussed. These issues include selection of a suitable edge detection method, construction of the illuminator and selection of the optimal positions of the light sources.

3.1. Edge detection method

The positions x_C and y_C of the measured object are determined using the positions of the edges in the intensity distribution (e.g. positions x_{11} and x_{12} in (1) and (2)). Hence, the precise determination of these positions is crucial from the point of view of good measurement accuracy.

In case of measuring methods that apply an imaging sensor without lens, the conventional edge detection methods (e.g. the Canny edge detector [3]) are not applicable. These methods were developed for 2D images and they are usually based on the first or the second derivative. For the purposes of the triangulation method, these edge detection methods are too complex because the triangulation method works with only one-dimensional signals. Moreover, these edge detection methods were designed for images acquired using cameras equipped with lens. In case of the triangulation method, the physical principles that form the image on the sensor are different which is especially apparent when measuring objects with small dimensions (in the order of 100 μm) and when using coherent light sources such as laser diodes.

Based on this analysis, the so-called thresholding method was selected for the determination of the edges' positions. The thresholding method determines the position of the edge as the point of intersection of the intensity distribution I_{REL} with a certain thresholding level – see Fig. 4 (the relative intensity I_{REL} is defined as the actual intensity distribution divided by the intensity distribution of an unobscured sensor).

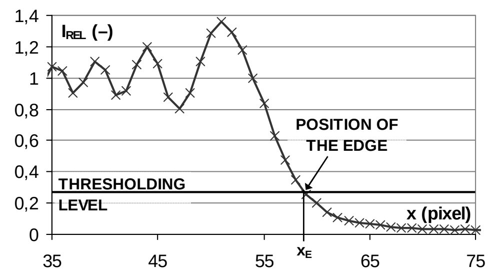

Fig. 4. Thresholding edge detection method.

Detailed description of the issues encountered when using the thresholding method (especially the selection of the thresholding level) as well as the analysis of uncertainty of edge detection using this method can be found in [2].

3.2. Construction of the illuminator

The triangulation method requires two point light sources to illuminate the measured object. When selecting a suitable light source, the most crucial parameter its light emitting area, which should be as small as possible.

From the comparison of the measurement results obtained using various light sources it followed that the laser diodes are the most suitable for the construction of the illuminator. Laser diodes, in contrast to e.g. LEDs, do not contain any lens or reflector. Consequently, since their light-emitting area is given only by the light-emitting area of the diode's chip it is typically in the order of 1 µm^2. Also the laser diodes have a narrower emission spectrum which results into sharper edges in the intensity distribution and consequently lower uncertainty of edge detection. The selected laser diode SLD6505A has a dominant wavelength of 650 nm and output optical power of 5 mW which is sufficient for the purposes of the triangulation method.

When using laser diodes as point light sources, the intensity distribution on the imaging sensor depends on the diode's driving current (Fig. 5). When driving a laser diode with a current above the diode's threshold current, the stimulated emission participates more on the total emission and the light emitted by the laser diode is more coherent. The resulting peaks and local non-uniformities in the intensity distribution (see Fig. 5b) may disrupt the edge detection. Therefore, the laser diodes should be driven by current below the threshold current level.

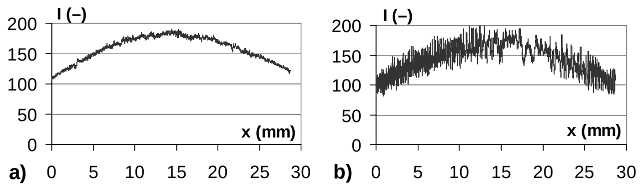

Fig. 5. Intensity distributions obtained using a laser diode: driving current a) below the threshold current; b) above the threshold current.

Also the orientation of the laser diode with respect to the imaging sensor has to be taken into account. Fig. 6 depicts the radiation patterns in two axes (axes *x* and *z*) of a laser diode SLD6505A driven by a sub-threshold current. From this figure it follows that the radiation angle is significantly bigger in one of the diode's axes (in this case it is the axis *x*). This axis should be oriented in the direction of pixels of the linear CCD sensor.

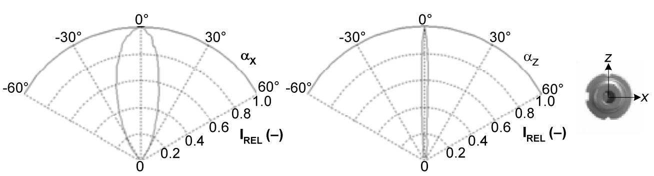

Fig. 6. Radiation pattern of the laser diode SLD6505A.

3.3. Selection of the optimal positions of the light sources

The selection of the light source's longitudinal positions L_1 and L_2 has several effects on the performance of the triangulation method. It affects mainly:

a) non-linearity of the method,
b) uncertainty of position determination and
c) dimensions of the measuring area.

The positions L_1 and L_2 affect the position measurement in both axes. In this paragraph, the effects are explained using the measurement in the direction of axis *x*; the particularities of the measurement in the direction of axis *y* are mentioned where appropriate.

A) Non-linearity

When using point light sources, the intensity distribution across the imaging sensor is always more or less non-uniform. The degree of non-uniformity depends on the distance between the light source and the sensor (distance y_2). It also depends on the horizontal distance between the light source and the point of observation because the intensity level decreases when going farther from the light source. Fig. 7 shows a comparison of intensity distributions obtained using a point light source placed approximately above the centre of the sensor (curve ①) with a distribution obtained using a light source placed above the beginning of the sensor (curve ②). In both cases the distance y_2 was adjusted to 84 mm.

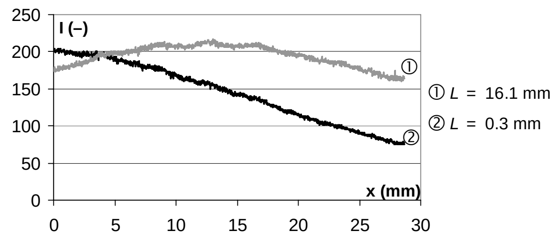

Fig. 7. Intensity distributions obtained for different horizontal positions of the light source

When both light sources are placed close to each other above one end of the sensor, it results into low illumination of the sensor's other end in both measurement steps. This leads to higher non-linearity of position measurement in the area of low illumination (see curve ① in Fig. 8). The curve ② in Fig. 8 shows the non-linearity $\Delta_{LIN}(x_C)$ obtained in case the positions of light sources were selected to secure higher and more uniform illumination of the sensor. In the second case, the non-linearity is significantly smaller.

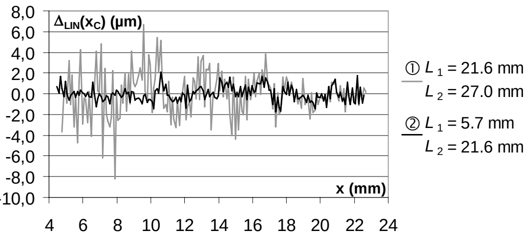

Fig. 8. Positions of the light sources and their influence on non-linearity of position measurement

The selection of light sources' positions should secure sufficient illumination of every part of the sensor at least in one of the two measurement steps. E.g. both light sources should be placed close to the centre of the sensor or one of them should be placed above the sensor's beginning and the other above sensor's end.

In case of very small distances y_2 (e.g. $y_2 \leq 50$ mm) it might not be possible to ensure sufficient illumination of every part of the sensor. In such case, techniques like adaptive adjustment of the exposure time might be necessary. The principle of this technique is shown in Fig. 9. Fig. 9a shows the intensity distribution when the distance y_2 was adjusted to 37 mm. Note that the left part of the sensor is close to saturation (saturation level was 255) but the part of the sensor with the measured object's shadow is poorly illuminated which may lead to high non-linearity of position measurement. In order to overcome this issue the sensor's exposure time (T_{EXP}) can be prolonged. The result is shown in Fig. 9b. The area with the shadow is now sufficiently illuminated; however, the other part of the sensor became saturated. Therefore, this technique is only applicable with sensors with the so-called anti-blooming feature [4]. Otherwise, the charge from the saturated part of the sensor could affect the signal in other parts of the sensor and distort the intensity distribution in the area of the shadow.

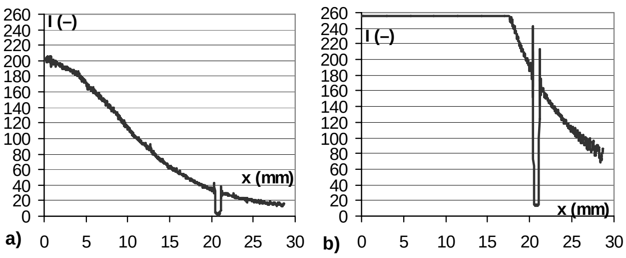

Fig. 9. Adaptive adjustment of the exposure time a) T_{EXP} = 25 ms; b) T_{EXP} = 140 ms

B) Uncertainty

The longitudinal positions of the light sources also affect the uncertainty of position determination though in case of position measurement in the direction of axis x the effect is not as strong as in the case of non-linearity.

The uncertainty of position measurement in the direction of axis x is higher when the longitudinal distance between the measured object and both light sources is bigger. E.g. in case both light sources are placed above the sensor's beginning, the uncertainty at the sensor's end will be several percents (up to 20%) higher than the uncertainty right under the light sources.

In case of measurement in the direction of axis y the uncertainty depends on the distance between the two light sources (the uncertainty is higher when the distance $L_2 - L_1$ is smaller).

In both cases the optimal configuration of the light sources would be: first light source placed above sensor's beginning, the second one placed above sensor's end.

C) Measuring area

In paragraph 2.2 it was shown how the positions of the light sources affect the size of the measuring area. From Fig. 3b and from (4) and (5) it follows that the measuring area will be the biggest when the distance between the two light sources is minimal ($L_2 - L_1 \to 0$). Therefore, from the point of the measuring area the light sources should be placed close to each other and preferably above the sensor's centre (in that case the measuring area will be symmetrical).

From the previous analysis it follows that each of the three considered parameters has different and often contradictory requirements on the longitudinal position of the light sources. Therefore, the selected combination of positions is a result of a compromise between these requirements. In measurements presented in this paper, the longitudinal positions of the light sources were adjusted to $L_1 = 5.7$ mm and $L_2 = 21.6$ mm. This combination ensures approximately uniform and sufficient illumination of the sensor and reasonably low uncertainty. The height of the measuring area in this case is $H = 54$ mm, the maximum width of the measuring area (given by the width of the employed CCD linear sensor) is $W = 28.7$ mm.

4. EXPERIMENTAL RESULTS

The schematic diagram of the measuring set-up used to verify the proposed method is depicted in Fig. 10. The distance between the sensor and the illuminator was adjusted to $y_2 = 84$ mm. The light sources' longitudinal positions were adjusted to $L_1 = 5.7$ mm and $L_2 = 21.6$ mm. The standard uncertainty of determination of positions L_1, L_2 and y_2 was 0.3 mm. DSP-based measuring CCD camera [5] equipped with the Analog Devices ADSP-2184 and with the linear CCD sensor Sony ILX551A was applied. The illuminator was built using laser diodes SLD6505A.

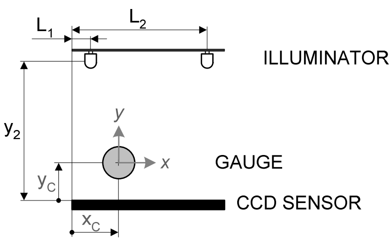

Fig. 10. Schematic diagram of the measuring set-up

The test objects (precision cylindrical gauges with nominal diameters d_{NOM} of 500 µm, 1 mm and 5 mm; $u(d_{NOM}) = 0.6$ µm) were moved in the direction of axes x and y using two interlocked positioning tables. In each adjusted position, the gauge's positions x_C and y_C were determined using equations (1) and (2). In each direction, the absolute deviations $\Delta_{LIN}(x_C)$ and $\Delta_{LIN}(y_C)$ were calculated. These deviations were calculated as a deviation of the measured position (x_C or y_C) from a line best-fitted on dependencies $x_C = f(x)$ and $y_C = f(y)$ (x, y are the positions of the measured object adjusted using the positioning table).

4.1. *Position measurement in the direction of axis x*

Fig. 11. depicts a typical graph of the non-linearity $\Delta_{LIN}(x_C)$ obtained with a 1 mm gauge placed in distance y_C = 5 mm from the sensor.

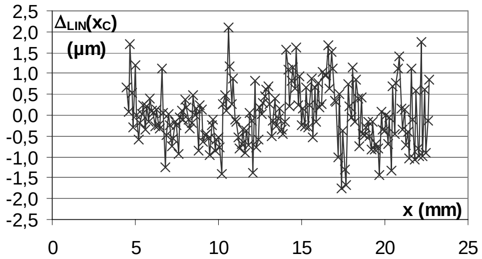

Fig. 11. Position measurement in the direction of axis *x* of a 1 mm gauge – non-linearity $\Delta_{LIN}(x_C)$

Table 1. shows a summary of maximum non-linearity $\Delta_{LIN}(x_C)$ and maximum combined standard uncertainty $u_C(x_C)$ obtained with three cylindrical gauges in three different distances between the gauge and the sensor (y_C).

Table 1. Summary of measurement results – measurement in the direction of axis *x*.

d_{NOM}	y_C	$\Delta_{LIN}(x_C)$ (μm)	$u_C(x_C)$ (μm)
500 μm	5 mm	2.2	16.7
	10 mm	3.7	32.3
	15 mm	3.1	50.7
1 mm	5 mm	2.1	17.3
	10 mm	3.8	32.5
	15 mm	4.4	51.6
5 mm	5 mm	3.3	24.2
	10 mm	3.2	38.8
	15 mm	4.0	58.0

From Table 1. it follows that the non-linearity $\Delta_{LIN}(x_C)$ is slightly higher in case of bigger distances y_C. There seems to be no significant dependence of $\Delta_{LIN}(x_C)$ on the measured object's nominal diameter d_{NOM}.

The uncertainty $u_C(x_C)$ increases when increasing the distance y_C due to the increasing sensitivity coefficients associated with the longitudinal positions of the light sources (L_1, L_2). The higher $u_C(x_C)$ in case of bigger objects is caused by the higher sensitivity coefficient associated with the distance between the light source and the sensor.

The relatively high uncertainty $u_C(x_C)$ is caused mainly by high uncertainties associated with the positions of the light sources ($u(L_1) = u(L_2) = u(y_2) = 0.3$ mm) in the employed experimental set-up. In the prototype of a measuring instrument that is in development in these authors' lab, uncertainties $u_C(x_C)$ at least 2 or 3-times smaller should be achievable.

4.2. *Position measurement in the direction of axis y*

Compared to the position measurement in the direction of axis *x*, the measurement in the direction perpendicular to the sensor (axis *y*) is less precise. Especially the non-linearity $\Delta_{LIN}(y_C)$ is significantly higher. Fig. 12 shows a typical graph of non-linearity $\Delta_{LIN}(y_C)$ obtained with a 1 mm gauge.

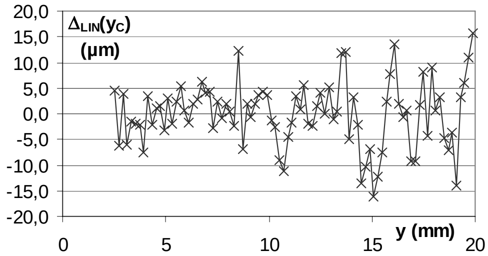

Fig. 12. Position measurement in the direction of axis *y* of a 1 mm gauge – non-linearity $\Delta_{LIN}(y_C)$

The non-linearity $\Delta_{LIN}(y_C)$ does not depend on the position of the object along the sensor (i.e. $\Delta_{LIN}(y_C)$ is the same regardless the *x* coordinate of object's position). However, $\Delta_{LIN}(y_C)$ depends on the measuring range (i.e. on the maximum y_C) as it can be seen from Table 2.

Table 2. Summary of measurement results – measurement in the direction of axis *y*.

d_{NOM}	$y_{C,MAX}$	$\Delta_{LIN}(y_C)$ (μm)	$u_C(y_C)$ (μm)
500 μm	10 mm	9.2	43.8
	15 mm	18.6	62.9
	20 mm	21.9	80.5
1 mm	10 mm	10.3	41.8
	15 mm	13.3	60.8
	20 mm	16.1	79.3
5 mm	10 mm	9.6	44.0
	15 mm	12.0	62.4
	20 mm	16.0	80.6

Both non-linearity $\Delta_{LIN}(y_C)$ and combined standard uncertainty $u_C(y_C)$ do not depend on the measured object's nominal diameter d_{NOM}.

When increasing the distance between the sensor and the object (y_C), the uncertainty $u_C(y_C)$ increases due to the increased sensitivity coefficients associated with the positions of the light sources (L_1, L_2, y_2).

As in the case of measurement in the direction of axis *x*, the high uncertainties are in this case caused mainly by high uncertainties associated with the positions of the light sources. Furthermore, in case of measurement in the *y* direction the inaccuracy in adjustment of the distance y_2 causes multiplicative deviation in position determination. The displacement of the illuminator in the direction of axis *y* by 1 mm results in relative multiplicative deviation of approximately 1.5%.

5. CONCLUSION

The proposed measuring method (the so-called *triangulation method*) enables to determine the position of an object with circular cross-section in two axes using a simple measuring set-up which consist of a linear sensor and two point light sources. The measuring set-up uses no optical elements such as lenses. The two-dimensional position measurement using a linear CCD sensor is possible thanks to the divergent beams emitted from a point light source.

The performance of the triangulation method was evaluated in a measuring area approximately 20 × 20 mm big. Within this area, the described method achieved non-linearities below 4.5 µm in the direction of axis x and below 22 µm in the direction of axis y.

Relatively high uncertainties of position determination were caused by high uncertainties associated with the positions of the light sources (L_1, L_2, y_2) in the employed experimental set-up. The prototype of a measuring instrument that is being developed should be able to achieve significantly better results.

The measurements (especially the position measurement in the direction of axis x) were also affected by the resolution the optical encoders used to measure the actual position of the positioning tables (the resolution of the encoders was 1 µm). It is assumed that the triangulation method is able to achieve even lower non-linearities; however with available equipment it was not possible to prove it.

Compared to dimension measurement using the triangulation method [2], the position measurement is significantly more sensitive to the precise adjustment of the light sources' positions (L_1, L_2, y_2). In the presented measurements, the uncertainties associated with these positions represented a major part of the overall uncertainty.

Besides the higher non-linearity in the direction of axis y the presented method has a smaller measuring area compared to conventional solutions. Despite these drawbacks, the proposed method is considered to be useful thanks to the good results of position measurement in the direction of axis x and thanks to the simple and small measuring set-up that is required.

The triangulation method is not limited to object's with circular cross-section and it can be extended to other shapes of measured objects.

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