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SIMPLE DEVICE FOR SMALL DIMENSION MEASUREMENT USING CCD SENSOR

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Abstract - The dimension of a measured object is determined from its shadow projected on a CCD sensor. A light source of parallel beams is usually applied in this case. To achieve such light source quality, an optical system with lenses has to be used. It increases its dimension and its price. The published solution applies one or several point light sources and a CCD sensor without lens. It enables to reduce both a dimension and a price of device.

Keywords: dimension measurement, CCD sensor, point light source

1. INTRODUCTION

The number of devices with a CCD sensor uses for contact-less dimension measurement the image of a measured object. In this case they must be equipped with lens (see Fig. 1).

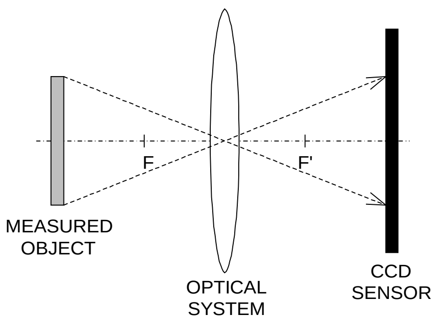


Fig. 1. Measurement system equipped with lens

The distance between the CCD sensor and the measured object is in this case equal or greater than 4 focal lengths of used lens. Other disadvantage is a change of magnification when the measured object moves along the optical axis [1]. When a small object is measured and a short distance between the measured object and the sensor is required, a method that uses a back lightning can be applied.

In this case a dimension of the measured object can be determined from a dimension of a shadow projected by the object on the CCD sensor without lenses. A light source of parallel beams is usually used for this application (see Fig. 2) [2]. Construction of such source requires nevertheless again an optical system. It increases (same as in the previous case) both a size and a price of the device.

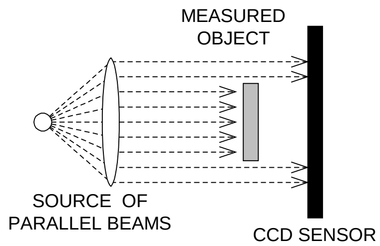


Fig. 2. Measurement system with light source of parallel beams

However, the more simple solution, which applies one or several point light sources, can be applied for small dimension measurement (see Fig. 3).

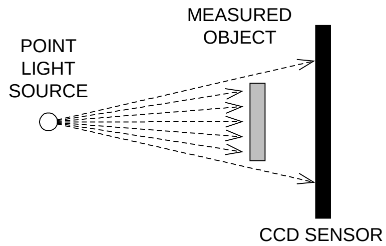


Fig. 3. Measurement system with point light source

It enables to reduce both a dimension and a price of device. There is one disadvantage of this method - the dimension of the measured object must be computed using a more complex formula than using the light source of parallel beams. However, a microcontroller (which is anyway used in control and/or measuring system) can be applied for this purpose.

2. SYSTEM WITH ONE POINT LIGHT SOURCE AND LINEAR CCD SENSOR

Using a point light source, the size of a shadow, which the measured object projects on a linear CCD sensor, has not the same dimension as the measured object (see Fig. 4). This is caused by the divergence of light beams emitted from the point light source. The real size of the object can be calculated from the shadow dimension and the distances light source - sensor, and object - sensor. The shape of the object has to be also taken into account, of course.

In the simple case, when the object has a rectangular cross-section, the following formula can be used:

$$x = (m_s - k_s)\,p = (m - k)\left(1 - \frac{d_1}{d_2}\right)p \qquad (1)$$

where p is the pixel distance, and the connotation of the variables follows from the Fig. 4.

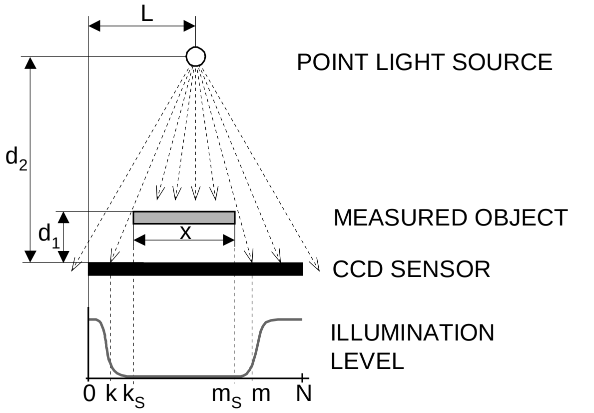


Fig. 4. Dimension measurement using a point light source – object with a rectangular cross-section

In the case of a circular cross-section of the measured object the measured dimension (radius) can be determined using following equation:

$$r = \left| \frac{(d_1 - d_2)\left[\sqrt{d_2^2 + p^2(L-k)^2} - \sqrt{d_2^2 + p^2(L-m)^2}\right]}{(2L - k - m)p} \right| \qquad (2)$$

where p is the pixel distance and the connotation of the variables follows from the Fig. 5.

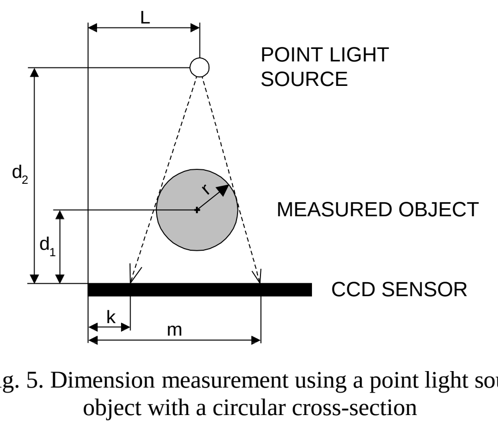


Fig. 5. Dimension measurement using a point light source – object with a circular cross-section

3. TRIANGULATION METHOD

The weak point of the method mentioned above pivots on the fact that the distance between the measured object and the sensor must be known. This disadvantage can be eliminated using two (or more) point light sources (see Fig. 6).

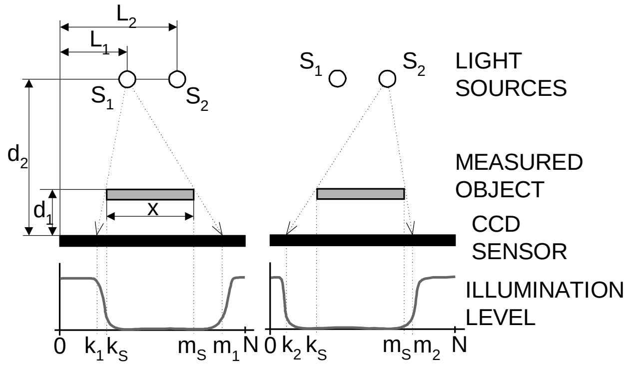


Fig. 6. Dimension measurement using a triangulation method

Using this method, a measurement consists of two steps. The light source S_1 is on and the source S_2 is off in the first step. Positions of edges (boundaries between light and shadow on the CCD sensor) k_1 and m_1 are measured. In the second step the light source S_1 is off and the source S_2 is on and the positions of edges k_2 and m_2 are measured. Finally, the measured dimension is determined from positions of these edges and from position of the light sources L_1 and L_2.

This situation is shown in Fig. 6 and it is described by following equations:

$$\frac{L_1 - k_1}{d_2} = \frac{k_S - k_1}{d_1} \qquad \frac{L_2 - k_2}{d_2} = \frac{k_S - k_2}{d_1}$$
$$\frac{m_1 - L_1}{d_2} = \frac{m_1 - m_S}{d_1} \qquad \frac{m_2 - L_2}{d_2} = \frac{m_2 - m_S}{d_1} \qquad (3)$$

From these equations we derived the resulting formula:

$$x = \left(\frac{L_1 m_2 - L_2 m_1}{L_1 - L_2 + m_2 - m_1} - \frac{L_2 k_1 - L_1 k_2}{L_2 - L_1 + k_1 - k_2} \right) p \qquad (4)$$

where p is the pixel distance, and the connotation of the variables follows from the Fig. 6.

Equation (4) is valid for an object with a rectangular cross-section. How it follows from (4), the dimension determined using the triangulation method doesn't depend both on the distance light sources - CCD sensor and on the distance measured object - CCD sensor (with assumption that these distances don't change during the measurement).

4. DETERMINING THE SIZE OF THE SHADOW FROM THE CCD SENSOR'S OUTPUT SIGNAL

The boundary between the illuminated part and the overshadowed one of the sensor is not sharp and it is typically several pixels wide. The width of the boundary depends mainly on the light source quality (see section 5.1). The diffraction of the light on the edge of the measured object also affects this width.

The dimension of the measured object is determined from the distance between the boundaries (edges) of the CCD sensor's output signal (see Fig. 7 and 8). Their exact location is crucial to achieve good measurement accuracy.

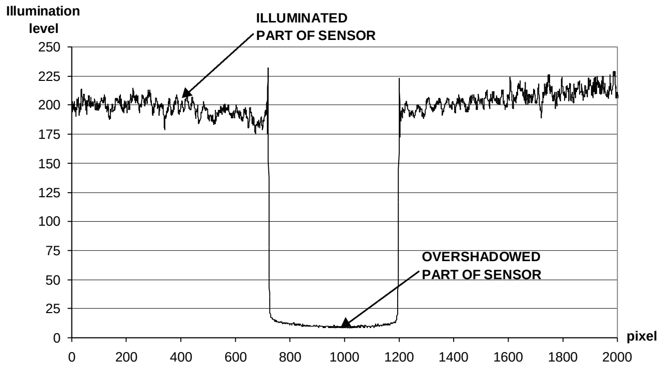


Fig. 7. Illumination profile on CCD sensor

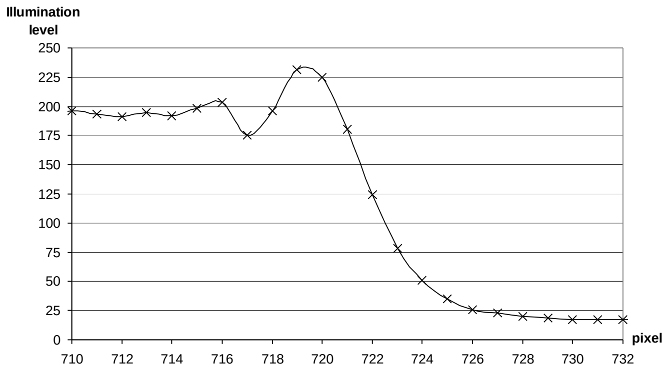


Fig. 8 Detail of edge in illumination profile

Several methods can be used to obtain these positions. The simplest one is based on comparing the sensor's output signal with a threshold level. The threshold level is usually set to 25% of the signal's amplitude (this level follows from an analysis of the light diffraction on the edge of the measured object illuminated by a light source of parallel beams). Since a digitised signal from the CCD sensor is processed, a linear interpolation between samples can be used to improve the resolution of this method.

5. ASPECTS OF IMPLEMENTATION

Several aspects must be considered implementing the method mentioned above.

5.1 Light source construction

The realization of the light source is essential for a good accuracy of measurement. The light source for the method mentioned above should be an ideal point light source. The real point light source has a finite area. The larger this area is, the wider will be the boundaries between the light and the shadow on the CCD sensor (see Fig. 9).

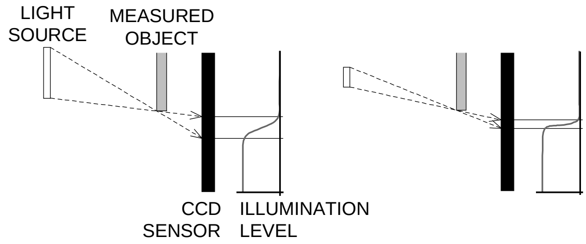
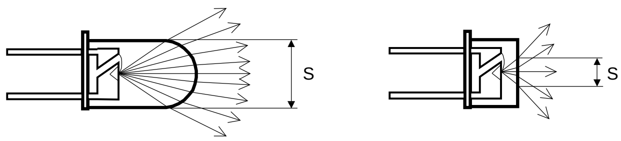


Fig. 9. Effect of light source's area on edge width

The width of the boundaries also increases when the distance between the measured object and the sensor increases or when the distance between the light source and the sensor decreases. The more the light source acts like a ideal point light source, the smaller the distance between the light source and the CCD sensor can be without decreasing the measurement's accuracy.

For a light source construction, standard LEDs can be used. For example, 3 mm LED with a water clear lens (e.g. Ledtech LT0373-41) or subminiature LED (e.g. Osram LGU260-EO) is applicable. In the case of 3 mm LEDs it is necessary to modify their radiation character by cutting their lens (see Fig. 10).



a) before lens cutting b) after lens cutting

Fig. 10. Effect of a lens cutting on the radiation character and the effective area *S*

Cutting the LED's lens, the effective area of the light source is decreased. An extended light source with a small area is obtained and it can be used instead of point light source.

5.2 Refraction of light in CCD sensor's cover glass

Because the angle between the beams and the plane of a CCD sensor is not perpendicular, a refraction in a cover glass of the sensor occurs (see Fig. 11).

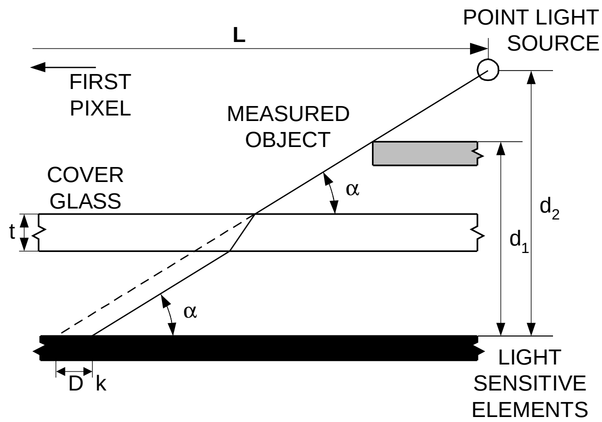


Fig. 11. Refraction of the light in the CCD sensor's cover glass

Consequently, the point of an incidence of the light beam on the sensor is changed by a distance *D*, in contrary to the case without the cover glass. The distance *D* can be determined using the formula:

$$D = t \sin a \left(\frac{1}{\cos a} - \frac{1}{n_\mathrm{r} \cos\left[\arcsin\left(\frac{1}{n_\mathrm{r}} \sin a \right) \right]} \right) \qquad (5)$$

where: $a \cong \mathrm{arctg} \frac{(L-k)p}{d_2}$,

n_r is the refraction index of the cover glass, *p* is the pixel distance, and the connotation of other variables follows from the Fig. 11.

6. SIMPLE DEVICE FOR DIMENSION MEASUREMENT

Mechanical construction for implementing the method mentioned above must ensure fixed distance both between the light source and the CCD sensor and between the measured object and the CCD sensor. Further, the sensor must be shielded from ambient light.

A simplified electrical block diagram of the developed device is shown in the Fig. 12.

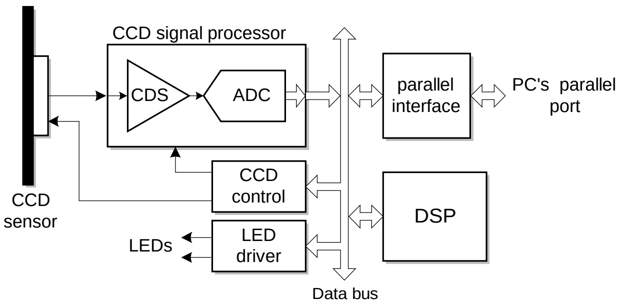


Fig. 12. Simplified electrical block diagram of device

The signal from the CCD sensor is brought to the input of a CCD signal processor AD9822. The CCD signal processor contains a correlated double sampler (CDS), an AD converter (ADC) and other blocks for the signal adjustment (a programmable gain amplifier and an offset DAC). The data from the CCD signal processor's output are read by the signal processor (DSP) ADSP-2184, which stores them in its internal RAM. DSP also generates control signals for the CCD sensor and the CCD signal processor.

This device was designed as a stand-alone. Still it can be connected to a PC. Device communicates with the PC using a parallel port working in the EPP (Enhanced Parallel Port) mode.

Software for both DSP and PC was designed. Current software for DSP implements functions for CCD control and communication with the PC. Software for the PC implements algorithms described in sections 2 and 3.

7. EXPERIMENTAL RESULTS

Measurements were accomplished with the linear CCD sensor Sony ILX551A. The light source was constructed using subminiature LEDs Osram LGU260-EO and was placed in the distance $d_2 = 66$ mm from the sensor. The distance between the measured object and the CCD sensor was adjusted to $d_1 = 2$ mm.

As measured objects wires with diameter from 98 μm to 1040 μm were used. Their true value of diameter was known with tolerance ±10 μm in case of 835 μm and 1040 μm wires and with tolerance ±2 μm for the thinner ones.

Absolute errors (Δ) and relative errors (δ) of measurement were determined from following equations:

$$\Delta x = x - x_\mathrm{C} \qquad (\mu\mathrm{m}) \qquad (6)$$

$$\Delta(2r) = 2r - x_\mathrm{C} \qquad (\mu\mathrm{m}) \qquad (7)$$

$$dx = \frac{\Delta x}{x_\mathrm{C}} 100 \qquad (\%) \qquad (8)$$

$$d(2r) = \frac{\Delta(2r)}{x_\mathrm{C}} 100 \qquad (\%) \qquad (9)$$

where x_C is wire's true value of diameter measured using a calliper, *x* is dimension of an object with a rectangular cross-section obtained using (1) and *r* is radius of an object with a circular cross-section obtained using (2).

7.1 Dimension measurement using one point light source

Table 1 shows results of dimension measurement in the case of a perpendicular illumination (it means that the join between the light source and the center of the measured object is perpendicular to the CCD sensor).

TABLE 1. Results of dimension measurement using one point light source

x_C (mm)	x (mm)	dx (%)	2r (mm)	d(2r) (%)
98	99,0	1,02	99,0	1,02
333	333,6	0,18	333,6	0,18
622	622,5	0,10	622,4	0,06
835	820,6	-1,72	820,2	-1,77
1040	1053,0	1,25	1052,6	1,21

In this case the effect of the measured object's shape can be neglected and (1) can be used for both rectangular and circular cross-section of the measured object. The Table 2 shows the differences between values obtain using (1) and (2) in case of non-perpendicular illumination.

TABLE 2. Results of measurement in case of non-perpendicular illumination

x_C (mm)	x (mm)	dx (%)	2r (mm)	d(2r) (%)
622	639,8	2,86	620,6	-0,23
835	877,8	5,13	824,1	-1,31
1040	1123,4	8,02	1055,1	1,45

The shape of object can not be neglected in this case.

The refraction of light in the CCD sensor's cover glass (see section 5.2) also affects measurement when using non-perpendicular illumination. Measurement results from Table 2 corrected using (5) are shown in Table 3.

TABLE 3. Results of measurement after correction of effect of refraction in CCD sensor's cover glass

x_C (mm)	x (mm)	dx (%)	2r (mm)	d(2r) (%)
622	642,2	3,25	622,9	0,14
835	881,6	5,58	827,2	-0,93
1040	1128,1	8,47	1059,1	1,84

It follows from Table 2 and Table 3, that the measurement is more affected by the shape of the measured object than by the refraction in the sensor's cover glass.

7.2 Dimension measurement using triangulation method

Results of dimension measurement using triangulation method are given in Table 4.

TABLE 4. Results of measurement using triangulation method

x_C (mm)	x (mm)	Dx (mm)	dx (%)
333	333,4	0,4	0,12
622	621,4	-0,6	-0,09
1040	1059,4	19,4	1,87

Equation (4) is valid for objects with a rectangular cross-section. Therefore in case of an objects with a circular cross-section there is an additional error of measurement caused by neglecting the object's shape. The bigger the diameter of the measured objects is, the bigger the error will be.

8. CONCLUSION

The device for one dimension contact-less measurement in the range of 100 µm to 1 mm using several point light sources and the relevant software were designed and developed. The method of measurement using one point light source and the triangulation method were developed and verified.

The point light sources were realised using miniature 1 mm LEDs (Osram LGU260-EO). The linear CCD sensor Sony ILX551A was applied. Digitised signal from the sensor was processed using digital signal processor ADSP-2184 and PC software we designed.

Several measurements using one point light source and the triangulation method were accomplished. Absolute errors of measurement were smaller than 2 µm using one point light source and smaller than 1 µm using the triangulation method for the lower end of range. For the higher end of range absolute errors were less than 15 µm using one point light source and less than 20 µm using the triangulation method. Typical relative errors lie in the range from 0,2% to 2%. More exact analysis of measurement errors will require more accurate instruments to measure the true value of dimension of the measured objects. In our case the uncertainty of determination of the measured object's dimension (calibration uncertainty) was comparable with found measurement errors.

The achieved results were found very good since no precise optics was used and since the device and mainly the light source were built using low-cost components. Better results can be obtained by building a light source with better parameters (e.g. using laser LEDs). Measurements using an area CCD sensor showed that this sensor could be used instead of linear CCD sensor as well.

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