The Triangulation Method of Contact-less Dimension Measurement Using an Area CMOS Imaging Sensor

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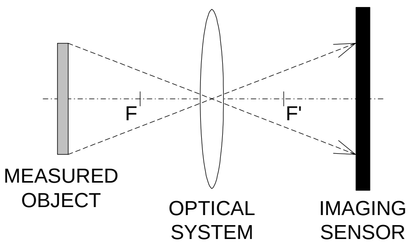
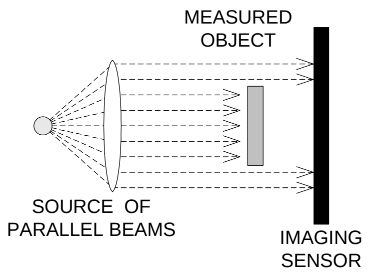
Abstract- The so-called triangulation method of contact-less dimension measurement determines the measured object's dimension from its shadow projected on an imaging sensor without lens. A point light source is used to illuminate the measured object. The so far used linear CCD sensors introduced a considerable uncertainty to the measurement. Application of area CMOS imaging sensors improves the measurement uncertainty and enables to use some new measurement methods. A special CMOS measuring camera was designed for this purpose.

I. Introduction

Common contact-less optical methods of dimension measurement use the image of the measured object to determine the object's dimension (Fig. 1a). An imaging element with lens is used for this purpose. The distance between the measured object and the sensor must be at least 4 focal lengths of the used lens resulting into significant dimensions of the measuring set-up.
The method that uses an imaging element without lens and a source of parallel beams to back illuminate the measured object (Fig. 1b) can be used in order to decrease the measuring set-up's dimensions. In this case, the object's dimension is determined from the shadow projected by the measured object on the sensor.



a) Measuring system equipped with lens



b) Measuring system with back illumination from a source of parallel beams

Figure 1. Two common concepts of a measuring system for contact-less dimension measurement

Further simplification of the measuring set-up can be accomplished by applying a modification of the previous method. This modification, proposed by the authors [1], uses one or more point light sources to illuminate the measured object. One of the modified methods is the so-called triangulation method of measurement.
This paper investigates the usage of an area CMOS imaging sensor for the so-called triangulation method of contact-less dimension measurement. In contrary to the so far used linear CCD sensor the CMOS area sensor offers several advantages: higher resolution (and therefore higher accuracy of measurement) and simpler interfacing and circuitry resulting into simpler and smaller measuring cameras.

II. Contact-less dimension measurement using imaging sensor without lens

The authors have earlier published [1] two novel methods of contact-less dimension measurement. Both methods apply an imaging element (such as a linear CCD sensor [2]) without lens and one or more point light sources to illuminate the measured object.

A. Dimension measurement using one point light source

The first measurement method uses one point light source to illuminate the measured object (Fig. 2).

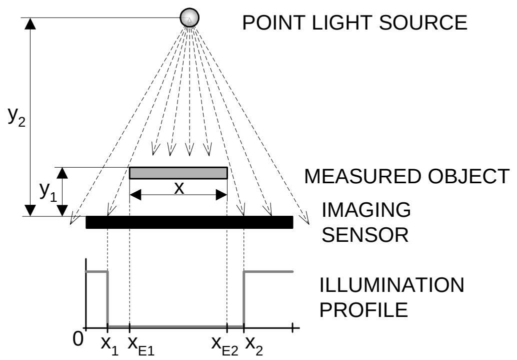


Figure 2. Measuring set-up for dimension measurement using one point light source

The measured dimension is determined from the dimension of the shadow projected by the measured object on the sensor and from the parameters of the measuring set-up using the following equation:

$$x = x_{E2} - x_{E1} = (x_2 - x_1)\left(1 - \frac{y_1}{y_2}\right) \quad (1)$$

where x_{E1}, x_{E2} are the actual positions of the measured object's edges
x_1, x_2 are the positions of the edges in the illumination profile
y_1 is the distance between the measured object and the sensor
y_2 is the distance between the point light source and the sensor

This solution compared to the common ones that use a source of parallel beams [3] enables to reduce the measuring set-up's dimension and price. However this method introduced a new disadvantage: the distance between the measured object and the imaging sensor (y_1) has to be known in order to determine the true object's dimension.

B. The triangulation method of dimension measurement

The disadvantage of the previous method is removed by the second method which adds a second point light source to the measuring set-up. The principle measuring set-up for this so-called triangulation method is shown in Fig. 3.

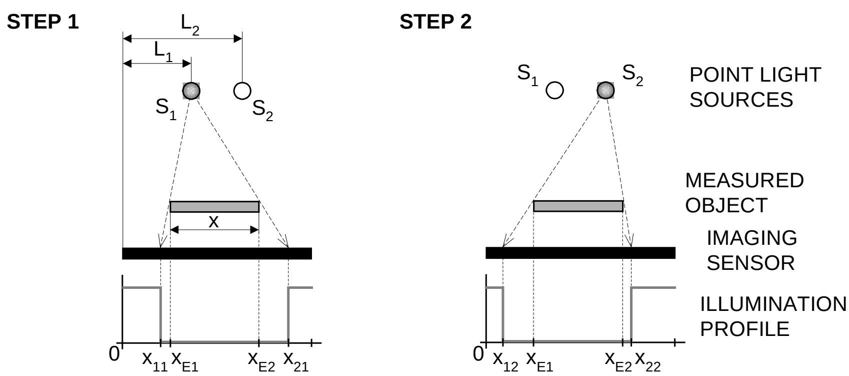


Figure 3. Measuring set-up for dimension measurement using the triangulation method

The object's dimension is determined from the positions of the edges in the illumination profile in the two measurement steps (in each step only one of the point light sources is on) and from the longitudinal positions of the light sources:

$$x = x_{E2} - x_{E1} = \left(\frac{L_1 x_{22} - L_2 x_{21}}{L_1 - L_2 + x_{22} - x_{21}} - \frac{L_2 x_{11} - L_1 x_{12}}{L_2 - L_1 + x_{11} - x_{12}} \right) \tag{2}$$

where x_{E1}, x_{E2} are the actual positions of the measured object's edges
x_{11}, x_{21} are the positions of the edges in the illumination profile in the first measurement step
x_{12}, x_{22} are the positions of the edges in the illumination profile in the second measurement step
L_1, L_2 are the longitudinal positions of the point light sources

Since the knowledge of the measured object's position is not required by this method (the position just has to remain unchanged during both measurement steps), the triangulation method is more suitable for practical applications than the method that uses one point light source.

III. Application of a CMOS imaging sensor for the triangulation method

The analysis of the measurement uncertainty of the triangulation method of dimension measurement has shown that the method is sensitive mainly to precise determination of the positions of the edges in the illumination profile (variables x_{11}, x_{12}, x_{21}, x_{22} in equation 2). Although methods that increase the accuracy of determination of these positions (e.g. interpolation) were applied, the uncertainty of determination of these positions is closely related to the pixel size of the used imaging sensor.
So far, a CCD camera with linear CCD sensors with pixel size 14 µm (e.g. ILX551A) was used for the triangulation method. To decrease the measurement uncertainty a sensor with higher resolution (i.e. smaller pixel size) has to be used. Although many linear CCD sensors have smaller pixels, the decision was made to use an area CMOS imaging sensor. Beside the smaller pixel size (usually 3-8 µm) the area sensors also enable to use signals from more image rows for measurement. Thus e.g. averaging can be used even when only one image is acquired. The measurement results can be therefore improved without executing multiple acquisitions. Other new techniques applicable with area CMOS sensors include e.g. windowing (definition of a region of interest - ROI) which enables to increase the sensor's read-out rate. The digital output of CMOS sensors is another advantage. Thanks to it, individual pixels can be distinguished in the sensor's output signal (this is not possible in case of area CCD cameras with analog output which are often used for measurement).

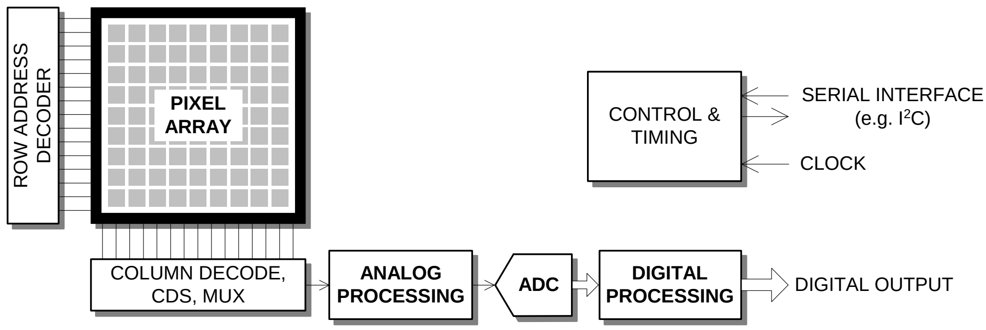


Figure 4. Block diagram of a typical CMOS imaging sensor

The CMOS imaging sensors contains several signal processing blocks (Fig. 4). Besides analog signal processing blocks (such as programmable gain correction) the sensor performs also digital signal processing. This includes e.g. correction of bad pixels and black level compensation. Since common CMOS imaging sensors are not designed for measurement purposes, a special care must be taken of these signal processing blocks since they can affect the measurement accuracy and validity. For example the bad pixel correction which replaces pixels with signal levels exceeding certain limits with the average level of surrounding pixels (various algorithms are used by the manufacturers) can alter significantly the sensor's output signal and has to be switched off in order to obtain undistorted results.

IV. DSP based measuring CMOS camera

Compared to CCD cameras (e.g. the measuring lines-scan camera presented by the authors [2]) a CMOS camera's design can be much simpler thanks to the specific features of the CMOS imaging sensors. The CMOS imaging sensors have digital output and therefore no external circuits such as correlated double samplers (CDS) or analog to digital converter (ADC) are required. These sensors also have fewer control signals than CCD sensors and these signals don't require drivers capable of driving

high-capacitance loads. Moreover, CMOS imaging sensors require only single supply voltage.
The described camera was designed especially for measurement purposes for both conventional methods of measurement and methods that use an imaging sensor without lens. The designed camera (Fig. 5) uses a monochrome 1/3 inch area CMOS imaging sensor LM9617 with resolution 648 × 488 pixels and pixel size 7.5 µm. Usage of a monochrome sensor for the measurements discussed in this paper is essential since color sensors have four times smaller resolution (four pixels with different color filters are required to form a single pixel of a color sensor).

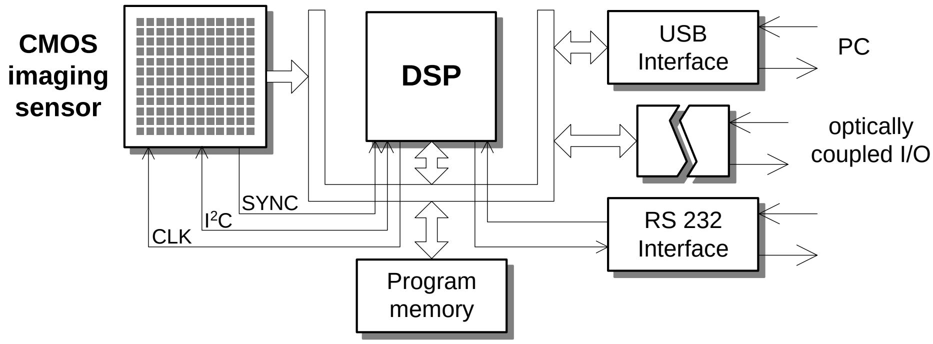


Figure 5. Block diagram of the designed measuring CMOS camera

The camera is controlled by a digital signal processor (DSP) ADSP-2185. The program running in the DSP reads the data from the CMOS sensor and sends them to the PC. Further, the program allows setting the parameters of the CMOS sensor (e.g. integration time) from the PC. Although there are few simple measurement algorithms implemented in the program, the algorithms described in this paper were implemented in the PC and performed on the images obtained from the camera.
The DSP and the CMOS sensor share the same clock signal so the execution of the program in the DSP and the sensor's operation are synchronous which enables to simplify the program. The three synchronization output signals of the sensor (vertical and horizontal synchronization and pixel clock) are connected to the DSP. These signals allow the program running in the DSP to identify the start of the image, start of each row and to distinguish individual pixels. The I^2C bus is used to set and read the sensor's parameters.
The camera can be interfaced with PC using the USB 2.0 (full-speed) or RS-232 interface. The USB interface, realized in the camera using the FT245BM chip, offers higher communication speeds than the RS-232 interface and is therefore more suitable for transmission of whole images from the sensor. The USB communication protocol always includes handshaking which secures reliable communication between the camera and the PC.
The imaging sensor is placed on a separate module (Fig. 6) so various sensors can be used in the future with the signal processing module.

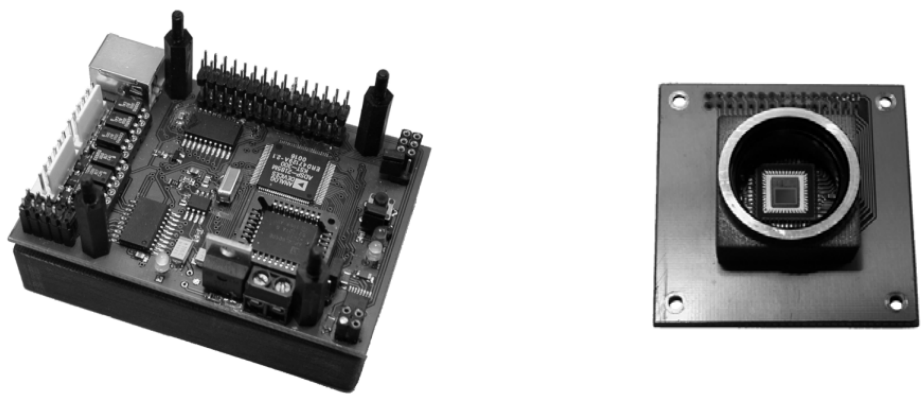
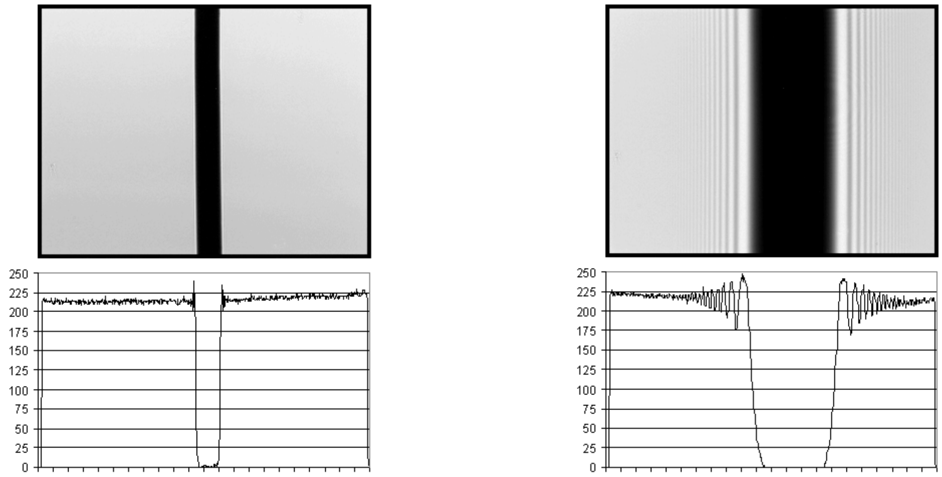


Figure 6. Designed measuring CMOS camera – DSP signal processing module and the module with the CMOS imaging sensor

V. Experimental and measurement results

The Fig. 7 shows typical images obtained when using the triangulation method of dimension measurement. Below the images, illumination profiles of one image row are shown.



a) measured dimension: 336 µm *b) measured dimension: 615 µm*

Figure 7. Example images and illumination profiles in selected row obtained using the designed measuring CMOS camera. Dark area is the shadow projected by the measured object.

The measured object's dimension is determined from the dimension of the shadow projected by the measured object. The shadow's dimension is obtained from the position of the edges in the illumination profile. The method that compares the illumination profile with a threshold level was used for this purpose. The threshold level was set to 25 % of the illumination level in the unobscured area of the sensor.

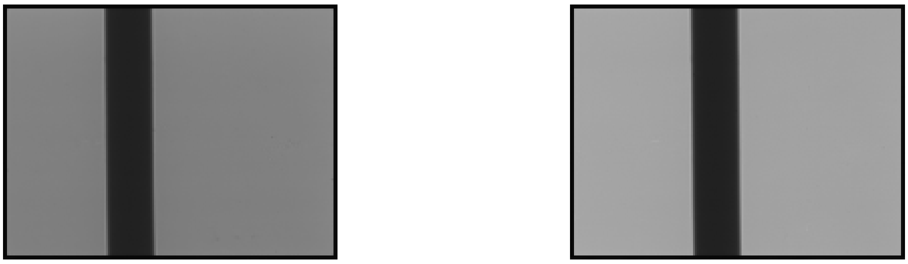


Figure 8. Images obtained in the two measurement steps of the triangulation method of contact-less dimension measurement

Since the above described triangulation method consists of two measurements steps, two different images have to be acquired and processed (Fig. 8). Due to the different longitudinal positions of the light sources used in each measurement step the shadow's position in the two images is different. The dimension of the projected shadow should be measured in the same row of both images.
In contrary to the linear sensor, the area sensor enables to use the illumination profile from multiple image rows for measurement. This enables to apply averaging even when only a single measurement was executed.

A. Measurement results

A series of dimension measurements were executed using the above described camera. In all below mentioned cases the distance between the sensor and the LED illuminator was set to 55 mm and the distances between the measured object and the sensor was adjusted to approx. 3 mm.
Table 1 shows measurement results for dimensions in the range from 100 to approx. 600 µm. In this case, the illumination profile of a single image row was used for the measurement.

Table 1. Measurement results obtained using the designed CMOS camera – measurement in a single image row

Measured object's dimension	**Measurement result** ***x*** **[µm]**
101 µm	98.8
336 µm	327.7
615 µm	607

Table 2 shows results when averaging in a single acquired image was used. The illumination profiles of eight neighbouring rows were used.

Table 2. Measurement results obtained using the designed CMOS camera – measurement in 8 neighbouring image rows

Measured object's dimension	**Measurement result** ***x*** **[µm]**	**Standard deviation of the measurement result** σ_x **[µm]**
101 µm	98.9	0.25
336 µm	327.4	0.31
615 µm	606	0.65

The following table shows the comparison of combined standard uncertainty of results obtained using the line-scan camera CCD [2] and the described CMOS camera. The CCD camera was equipped with a linear CCD sensor ILX551A which has pixel size of 14 µm while the CMOS camera used an area CMOS sensor LM9617 with pixel size 7.5 µm.

Table 3. Comparison of combined standard uncertainty u_C of measurement results obtained using CCD and CMOS imaging sensor

Measured dimension	u_C **[µm]**	
	Linear CCD sensor	**Area CMOS sensor**
101 µm	4.3	2.5
336 µm	5.6	4.2
615 µm	8	7

This comparison shows overall decrease of the combined standard uncertainty especially in the case of smaller dimensions.

VI. Conclusions

Measurement results obtained using the designed CMOS measuring camera proved that application of an area CMOS imaging sensor can improve the performance of the so-called triangulation method of contact-less dimension measurement. Applying this sensor enables to decrease the measurement uncertainty (thanks to its smaller pixel size). Further it enables to use some measurement methods that were not available when using a linear sensor (e.g. applying averaging in case of a single acquisition). However attention has to be paid to the signal processing units built into the CMOS sensor such as the bad pixel correction because they can affect measurement results. Also the smaller signal to noise ratio compared to the CCD sensors has to be taken into account.
Moreover, the CMOS sensors help to simplify the design of measuring cameras since these sensors require only single supply voltage, they have fewer control signals and no circuits such as samplers and ADC are required.

References

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