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LASER PROFILOMETERS FOR SURFACE INSPECTION AND PROFILE MEASUREMENT

Key words

Surface inspection, surface profile measurement, non-contact measurement, laser triangulation, laser profilometer, 3D surface visualisation.

Abstract

This paper presents the developed 3D profilometers for surface inspection and profile measurement based on the triangulation principle. The applied compact high-resolution laser triangulation sensors with the mechatronics positioning system and computer data analysis enable the surface profile reconstruction for applications in industry as well as in research. The application tests were done on various specimens. Suitable filters can be applied to eliminate signal noise and disturbances and to improve the computer image visualisation.

Introduction

Innovative non-contact measurement technologies are increasingly necessary for quality control in industry, maintenance checks and for research projects. There are a number of reasons to replace conventional contact measuring methods, such as CMMs, micrometers or stylus profilometers, by new approaches. Often contact methods are not applicable due to the fragile nature of the subject and the surface sensitivity to mechanical contact, very high or very low object surface temperature, very small object size, or the time limitation of measurement.

Thanks to achievements in optoelectronic technology during last dozen years, novel laser gages have been developed. The miniature optics, advanced microelectronics and signal pre-processing are applied in a new generation of compact laser measurement heads. Nowadays laser scanning systems with built-in novel measurement heads enable automated fast and high accuracy measurement of the surface profile and computer 3D surface data visualisation [8, 9, 10, 11, 12].

For industry and shop applications and research needs, the laser triangulation 3D profilometers were developed in the Dept. of Mechatronics of the Institute for Sustainable Technologies – NRI. The project included the numerous experimental tests of novel laser heads in several applications.

1. Laser triangulation principle

The laser triangulation principle is founded on the measurement of the angle of view of a laser beam spot projected onto the object surface (Fig. 1).

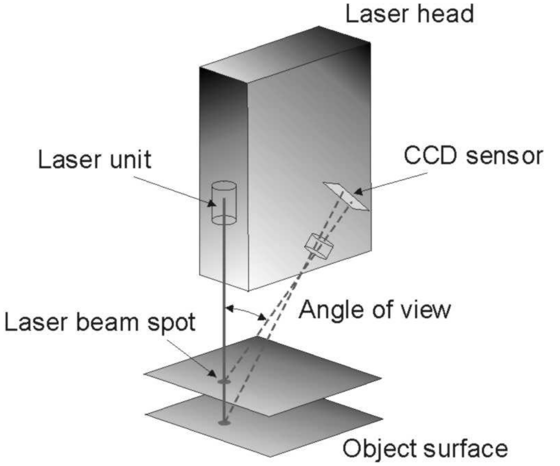

Fig. 1. Laser triangulation principle

The light quantity distribution of the reflected beam from the object is analysed and the CCD sensor detects the pixel with the laser light peak value. The position of the laser spot on the CCD sensor is related to the position of laser spot on the object surface (Fig. 2). When object is moved from position 1' towards 2', the laser spot displacement on the CCD sensor is equal *ds*.

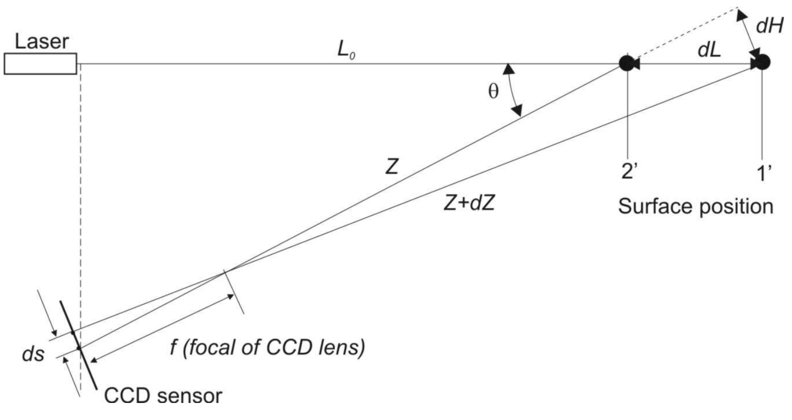

Fig. 2. Schematic of the triangulation measurement

The measurement sensitivity is expressed as a function of the triangulation angle Θ, the base distance Z and the focal distance f [1]:

$$\frac{ds}{dZ} = \frac{f}{Z} \sin \Theta \tag{1}$$

Usually, the compact laser sensors are characterised by the resolution given in the micrometer scale. For short ranges, laser triangulation sensors are capable to provide sub-micron resolution.

The laser triangulation is the point-based method. For the 3D visualisation of the inspected surface, the mechatronics units are used to perform the scanning process point-by-point. In the scanning process, the two-dimensional matrix is created from the recorded data as the digital presentation of the scanned surface. The data set is expressed as the following equation:

$$W = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} L_{ij} \right) \tag{2}$$

where:

i, j – row and column number;
L_{ij} – signal value at (i, j) point of scanned area.

There are limitations to the method caused by the nature of vision sensing which can influence the measurement results. The particularly significant effects are surface reflection, a different contrasting surface texture in the micro-scale, a shadow effect, laser beam disturbances at the edge of the object, light diffusion and absorption [1, 5]. For improving the image visualisation, data processing with the use of filtering functions is necessary. The well known methods involve point operations, convolution, non-linear filters, morphology, the FFT method and also the most advanced fuzzy logic and neural nets [7].

2. System structure

A system structure for the three-dimensional surface profilometry was developed (Fig. 3). The system includes hardware and software for the scanning process and computer 3D visualisation of the scanned object. The mechatronics systems were designed for precision positioning of the scanned object. In the X-Y surface profilometer, two linear stages were implemented. The mechatronics system of the circular R profilometer is equipped with a rotary stage and linear stage. For data acquisition from the laser head, a measurement PCI-bus card is used. For stage control, the PCI-1240 multi-axis card is applied. The modular structure enables the implementation of the various laser heads to develop OEM versions to meet the user's requirements.

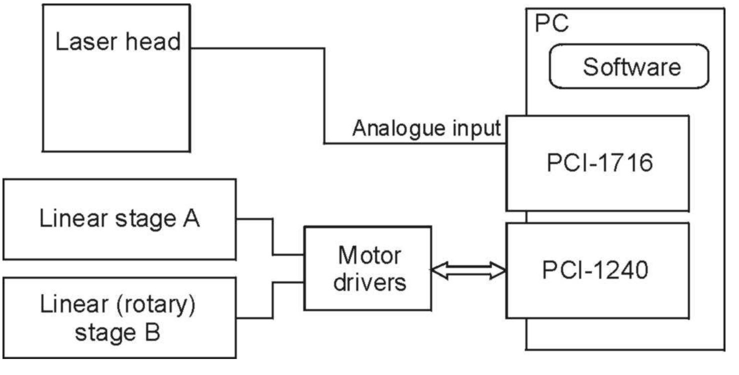

Fig. 3. System structure of laser profilometer

3. Developing the prototype versions of profilometers

The surface profilometer X-Y and rotary profilometer R were developed and equipped with high accuracy laser heads (Fig. 3). The modular constructions are based on standard aluminium profiles and accessories. The aluminium structure provides rigidity and assures the dampening of the vibration caused by the motorised stages.

a) b)

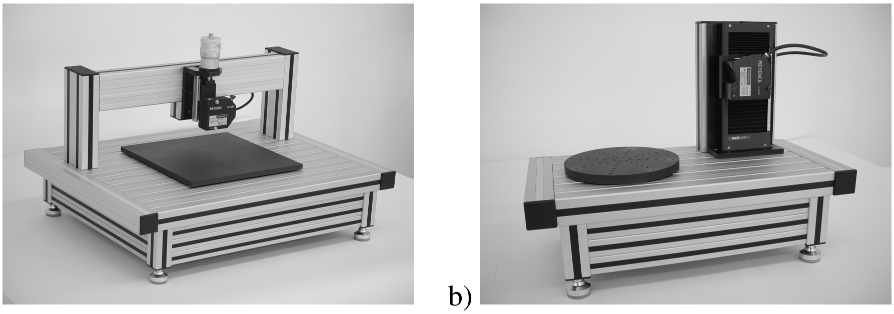

Fig. 4. Developed prototype versions: a) profilometer X-Y, b) profilometer R

For positioning the object in the range of 100mm x 100mm, the two-axis stage was applied in the profilometer X-Y. Linear drives and electronics circuits are mounted inside the housing. The adjustment of the working distance of the laser head is possible by using a manually operated micrometer head. In the rotary profilometer R, the rotary stage was applied for angle positioning the object towards the laser head. The laser head movement along the vertical axis is executed by the linear stage. The object is scanned along the programmed trajectory (Fig. 5). Table 1 presents the basic specifications of the profilometers.

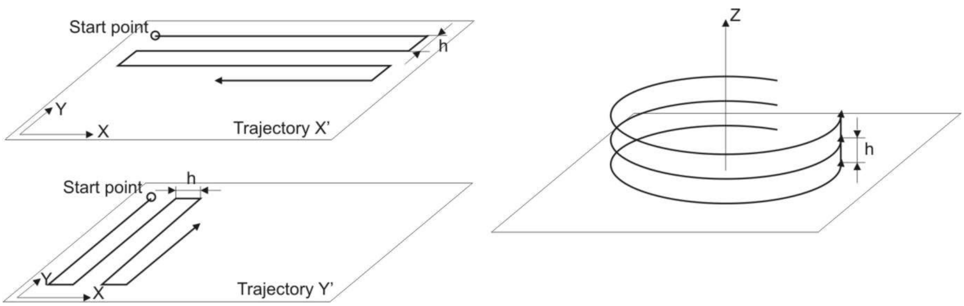

Fig. 5. Used scanning trajectories in the developed profilometers

Table 1. Profilometers specifications

Profilometer XY	Profilometer R
measurement range: 10 mm scanning area: 100x100 mm resolution: 1 µm scanning step: 0.6 µm ÷ 5 µm	Radial measurement range: 80 mm Vertical radial measurement range: 100 mm Resolution: 0.5 µm Vertical scanning step: 0.6 µm ÷ 5 µm Angular scanning step: 0.003° ÷ 0.027°

The developed software includes scanning control and visualisation modules. The scanning control module allows hardware initialisation, the set-up of scanning parameters (step size, drivers speed, scanning speed), calibration and filter set-up. The visualisation module includes function bookmarks that enable data processing and 3D presentation of a scanned surface. The interactive functions are available as follows: the selection of the angle of view, zoom, and the section of a surface. The data is generating in VRML and txt format. The scanning process is fully automated from the start command to the data stored on the computer disc.

4. Measurement accuracy tests

For the accuracy tests of the developed profilometer XY the sets of gauge blocks of the 0 grade (accuracy class) were used. The set of gauge blocks of 8 mm height was scanned in the area of 12x12 mm with the scanning step of 0.2 mm. The 3D visualisation of scanned object and the 2D section view created from 3D model were presented in Matlab (Fig. 6). The measured height of the set of gauge blocks was calculated as the average of results obtained in scanning process. The estimate was equal to 7.996 mm with the determined expanded uncertainty ± 0.020 mm (Table 2).

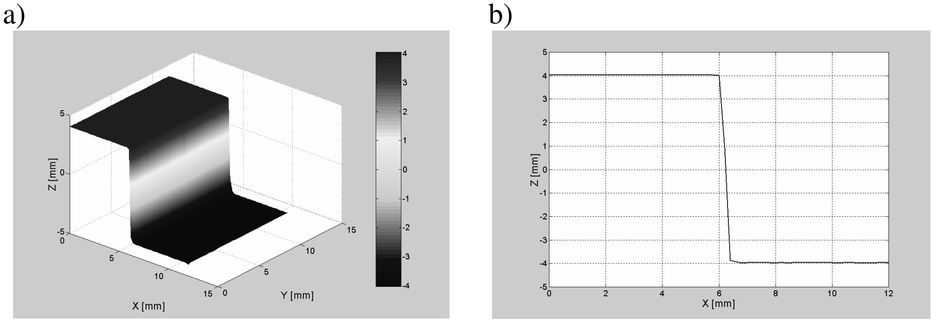

Fig. 6. Visualisation of scanned set of gauge blocks: a) 3D image, b) 2D view of the vertical plane section

The accuracy tests of the rotary profilometer R were performed for the diameter measurement. The cylinder was used as a gauge. In first step the cylinder's diameter was measured by a digital slide caliper. Using profilometer the cylindrical surface was scanned over a 300° in 1° steps in the horizontal plane and in the range of 10 mm in steps of 0.2 mm in the Z-axis. The 3D visualisation of the scanned cylindrical surface and the 2D section view in a horizontal plane were presented in Matlab (Fig. 7). The cylinder diameter was calculated as the average of the results obtained during scanning process. The estimate of the measured diameter was equal to 80.38 mm and the determined expanded uncertainty was equal to ± 0.16 mm (Table 2).

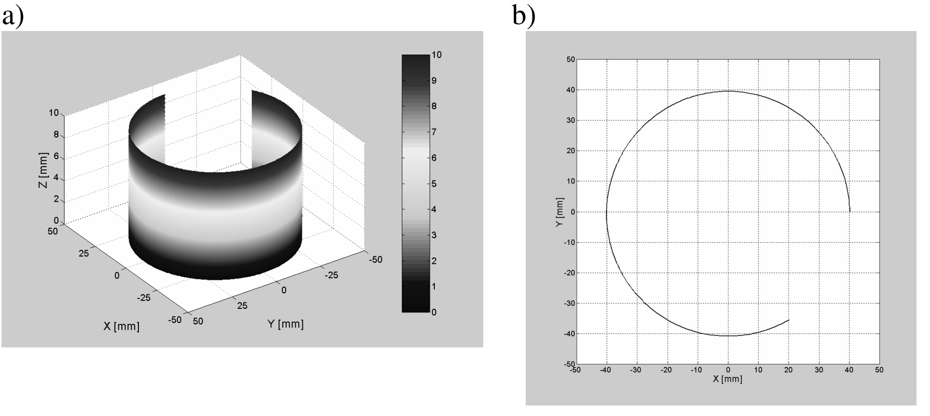

Fig. 7. Visualisation of the scanned cylinder: a) 3D image, b) 2D view of the horizontal plane section

The determined total uncertainty of the measurements includes [4]:

- uncertainty quantified by the calculation of the standard deviation from the a set of measurements known as type A evaluation;
- uncertainty expressed in the manufacturer's specifications of the applied laser sensors in profilometers (type B evaluation).

The total uncertainty of the measurements was expressed as the expanded uncertainty given by equation:

$$U = k \cdot u_c \tag{3}$$

where:

u_c – combined standard uncertainty,
k – coverage factor (in this case $k = 2$).

The coverage factor $k = 2$ defines the *level of confidence* of approximately 95% for probability distribution assumed to be normal. The combined standard uncertainty is expressed as follows:

$$u_c = \sqrt{u_1^2 + u_2^2} \tag{4}$$

where:

u_1 – uncertainty evaluated by statistical analysis (type A),
u_2 – uncertainty base on manufacturer's specifications (type B).

Table 2. Measurement results and calculated uncertainty

	Profilometer XY (set of gauge blocks)	Profilometer R (cylinder gauge)
Gauge value	8 mm (0 grade)	80.25 ± 0.02 mm
Measured value (best estimate)	7.996 mm	80.38 mm
Linearity of laser sensor (manufacture specifications)	±0.1% (0.020 mm)	±0.05% (0.080 mm)
Uncertainty type A (u_1)	± 0.008 mm	± 0.079 mm
Uncertainty type B (u_2)	± 0.006 mm	± 0.023 mm
Combined standard uncertainty	± 0.010 mm	± 0.08 mm
Expanded uncertainty (coverage factor k=2)	± 0.020 mm	± 0.16 mm
Measured value including uncertainty	7.996 mm ± 0.020 mm	80.38 mm ± 0.16 mm

5. Application tests results

Preliminary tests on the developed profilometers were performed in to experimentally examine the scanning process for numerous specimens. In the examples shown, properties of specimens were varied, such as, the shape, surface structure, the surface to reflect ability the laser light, material translucent, etc (Fig. 8 and Fig. 9).

It may be observed from the examples, that developed apparatus enable high accuracy surface inspection for identification and quantification in the defined area of interest. Due to nature of laser triangulation method, there are noisy signals and disturbance effects at surface ridges. Nonetheless, the applied method is a valuable alternative to the contact technique in the case of delicate parts and fragile surfaces.

The data matrix presentation enables image analysing using mathematical transformation. As shown in Fig. 10, in the image processing suitable filters can be effective. In the presented case the convolution filter was used.

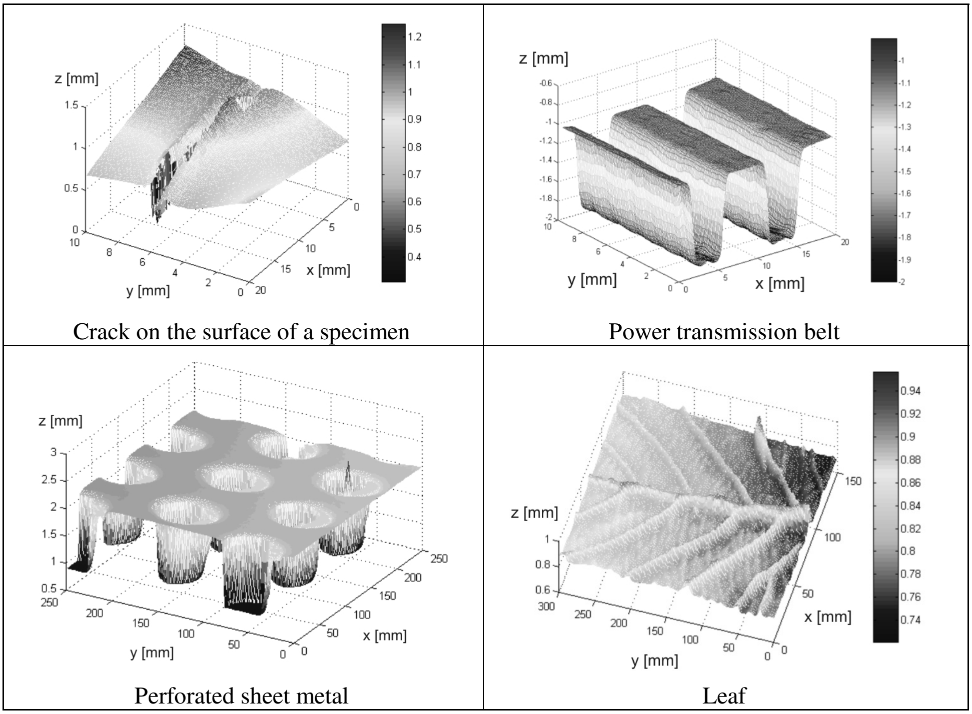

Fig. 8. Examples of the 3D visualisation using the Matlab and Mathcad formats

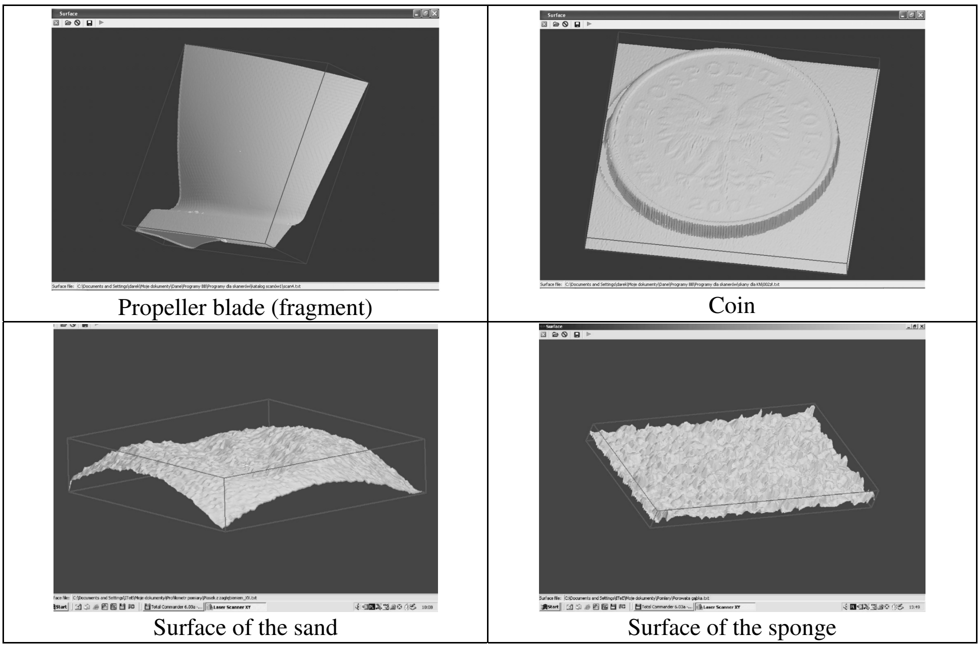

Fig. 9. Examples of the 3D visualisation and surface reconstruction

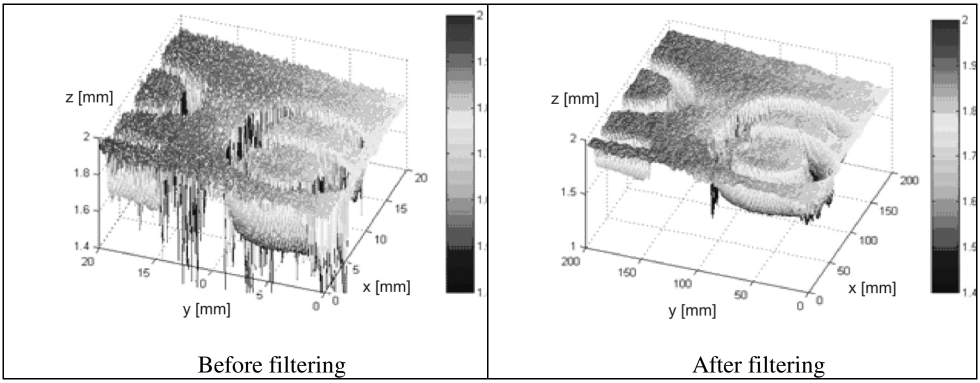

Fig. 10. Image cleaning using linear filter

The results of measurement tests with highly reflective metal surfaces have shown that the output signal trace contains disturbing peaks caused by reflection of the surface microstructure (Fig. 11). In the case of the applied laser head of the measured range of 10 mm, the identified and measured single peaks have a value up to 40 μm. For eliminating the peaks, the low band-pass filters and advanced analysing filters can be used.

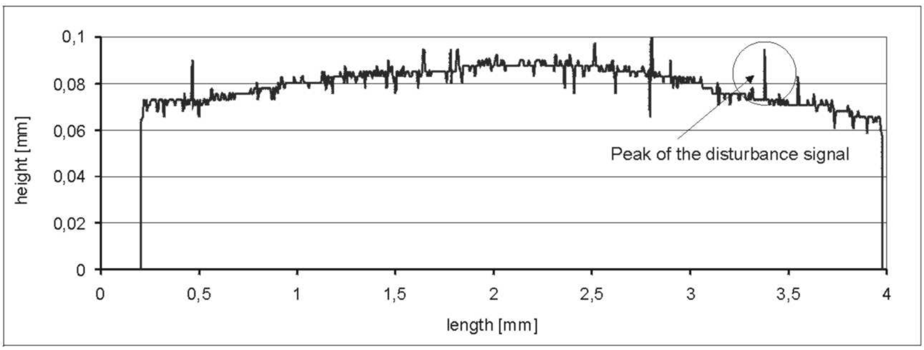

Fig. 11. 2D profilogram of the face profile of the surface piston ring

The high resolution scanning of maximum area range with the linear stage step of single micrometers and the 16-bit grey scale pixel values needs large hard disc memory up to 100 GB. In practice, during experimental tests for reducing the scanning and data analysing time, the resolution steps of tens or hundreds of micrometers where set up.

Conclusions

Experimental tests and obtained results have proven that the developed profilometers allow the surface inspection and 3D visualisation of a surface. The applied and tested laser heads offer high measurement accuracy in relation to the measurement range. When developing the laser triangulation profilometer, it is important to pay attention to the possibility to occur disturbing peaks that can reach a value of tens of micrometers. For improving the image visualisation, data processing using filtering functions is necessary.

Despite of their limitations, the developed laser triangulation profilometers are a valuable tools for application in a numerous areas of industry and research, such as, quality inspection, material engineering, tribology, MEMS engineering, medicine and biology, artwork [3, 5, 6].

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References

1. Bradshaw G.: Non-contact surface geometry measurement techniques. Technical Report TCD-CS 1999.
2. Chinga G., Gregersen Ø., Dougherty B.: Paper surface characterization by laser profilometry and image analysis. Journal of Microscopy and Analysis, 84: 5-7 (2003).
3. Godin G., Levoy M., Rioux M., Cournoyer L., Beraldin J.-A., Blais F.: An assessment of laser range measurement on marble surface. 5th Conference on Optical 3D Measurement Techniques, 2001, Vienn.
4. Guide to the Expression of Uncertainty in Measurement. International Organization for Standardization. 1995.
5. Lichti D. D., Harley B. R.: The effects of reflecting surface material properties on time-on-flight laser scanner measurements. Symposium on Geospatial Theory, Processing and Applications, Ottawa 2002.
6. Rozehnal D.: Experimental use of a triangular laser distance meter as a contactless sensor of deformations and vibrations. 33rd international conference and NDT exhibition Defectoscopy 2003, Ostrava 19-21.11.2003.
7. Tadeusiewicz R., Korohoda P.: Komputerowa analiza i przetwarzanie obrazów. Kraków, Wyd. Fundacji Postępu Telekomunikacji, 1997.
8. http://www.keyence.co.uk/products/vision/laser/laser.php

9. http://www.laser-ndt.com/index.html
10. http://www.lmint.com/
11. http://www.micro-epsilon.com/
12. http:// www.solarius-inc.com/

Reviewer:
Krzysztof PATORSKI

Profilometry laserowe do kontroli jakości i pomiarów profilu powierzchni

Słowa kluczowe

Kontrola jakości powierzchni, pomiar profilu powierzchni, pomiary bezkontaktowe, triangulacja laserowa, profilometr laserowy, wizualizacja powierzchni 3D.

Streszczenie

Artykuł przedstawia opracowane profilometry 3D do inspekcji powierzchni i pomiarów jej profilu w oparciu o zasadę triangulacji. Zastosowane triangulacyjne głowice laserowe wysokiej rozdzielczości z mechatronicznym systemem pozycjonowania i komputerową analizą danych umożliwiają odtwarzanie zarysu powierzchni do zastosowań w przemyśle i badaniach naukowych. Testy zostały wykonane na różnych próbkach. W celu eliminacji szumów oraz zakłóceń i uzyskania wizualizacji komputerowej zastosowano odpowiednie filtry.