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APPLICATION OF A LASER 2D TRIANGULATION METHOD FOR RECONSTRUCTION OF SURFACE GEOMETRY

Key words

Profilometry, 2D laser triangulation method, shadow effect, reconstruction of surface geometry.

Abstract

In the Department of Mechatronics at the Institute for Sustainable Technologies – NRI in Radom a laser profilometer with a 2D triangulation head was developed. The contactless method for distance measurement applied in the apparatus allows the scanning of a surface simultaneously in two directions and adds to the increase in the speed of the measurement process as compared to the alternative point-by-point methods. The characteristic feature of the profilometer is the proposed original measurement method that reduces the number of non-measurable points that occur during the measurement process. The general concept of the method consists in the multiple scanning of the surface of the tested object in selected directions. The obtained results of the partial measurements are analysed and combined to reconstruct the continuous surface of the tested products. The correctness of the method was verified based on experimental tests conducted for selected products of variable geometry.

Introduction

For the measurement of topography of the surface, the most widely used methods are contact methods. They have some disadvantages, such as the necessity of direct contact of the measurement device with the analysed surface, low pass speed, the high risk of damaging the tracing edge and the possibility of deformation or damage of fragile surfaces of the tested products [1, 2]. For that reason, for a number of years, efforts have been made to develop other methods for the analysis of the surface topography, which are alternatives to contact profilometry. The leading techniques use light as the carrier of information about the measured quantities, thanks to the rapid development of the optoelectronics and advances in microprocessor technologies. The optical contactless systems are based on the measurement of the reflection or diffusion of the light on the surface of the tested object [3]. The profilometers that have been developed in the Department of Mechatronics at the Institute for Sustainable Technologies – NRI in Radom use the precise point-by-point scanning method. In these apparatus, the measurement needle was replaced by a focused beam of light that traces the geometry of the surface point-by-point as a result of mutual movement of the measurement head and the tested surface. The main limitation of this method is the extended time need for the measurements. One of the aims of the realised work is the development of measurement methods that allow acceleration of the measurement process with the preservation of high accuracy. The applied optoelectronic contactless distance measurement method with the use of a 2D laser head allows th scanning of the surface simultaneously in two directions, which is distinguished by the high speed of the measurement process compared to the methods using point-by-point measurement [4, 5, 6].

1. The measurement method

In the systems that use the 2D triangulation method, the laser line is projected on the surface of the object. The line is created by passing the laser beam through the set of cylindrical lenses. The light reflected from the surface of the object passes through another set of lenses and falls on the light-sensitive CMOS matrix (Fig. 1). The variation of the distance from the observed surface in relation to the measurement head causes a variation in the angle of observation for the given point. As a result, the location of the beam falling on the CMOS matrix varies in relation to the location of the point on the object. During singular scanning, the set of points that constitute the length of the line projected on the object is returned [4].

The use of the set of cylindrical lenses causes that the shape of the emitted laser light is of the discrepant beam. That results in a variable measurement range along the projected line, depending on the height of the head over the tested object. The virtue of the 2D laser triangulation is the significant increase of scanning speed compared to point-by-point methods. For example, the measurement head used in the developed profilometer obtained from Keyence allows simultaneous measurement of 800 measurement points [4, 5, 6].

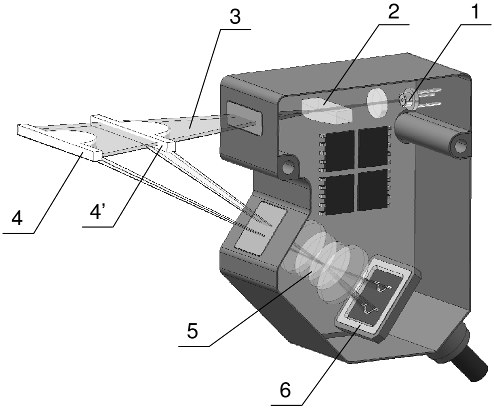

Fig. 1. The principle of measurement using the 2D laser triangulation: 1 – semiconductor laser, 2 – cylindrical lenses, 3 – laser beam, 4 – surface of the object (two different locations), 5 – set of lenses, 6 – CMOS sensor

2. The limitations of laser triangulation methods

Despite the number of virtues of the contactless measurement method, when using laser triangulation method, there exist limitations that emerge mostly from the nature of the optical measurement and the characteristic of the surface of the measured object. Out of the interfering factors, the most serious limitation is related to the appearance of large zones of shadow and to the multiple reflections from highly reflective edges [4]. The "shadow effect" is caused by the lack of the possibility of the observation of the reflected laser beam by the sensor caused by the covering of the observation field by the edge of the object or another obstacle (Fig. 2a) [3, 4, 5, 7, 8]. In the case of highly reflective surfaces, there may appear interferences in form of additional reflection from the edges. The reflections appear on the surface of the sensor and interfere with the measurement (Fig. 2b) [4, 5, 7]. In the case of 2D laser triangular heads, there also exists the disturbance in form of the "dead zone" (Fig. 2c). The "dead zone" disturbance increases with an increase in the distance between the measurement point and the centre of the measurement line [4, 5]. The edge of the object prevents proper lighting of whole area of the profile.

Sample profiles recorded for selected areas of the tested object are presented in Figure 3. Depending on the relative location of the scanned object and the measurement head, different interferences occur.

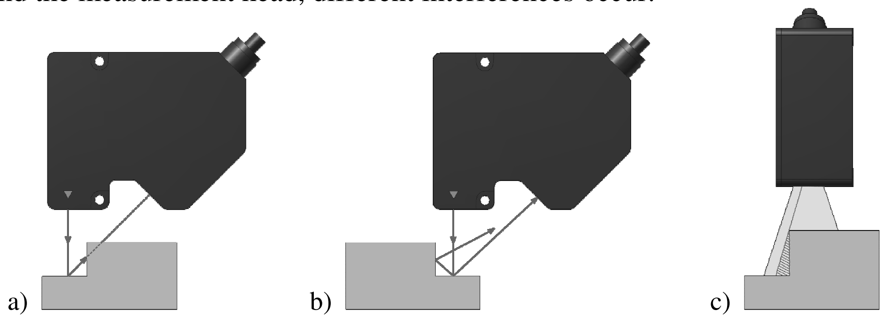

Fig. 2. Interferences of the measured data occurring in the laser triangulation method [4]: a) the “shadow effect,” b) additional reflections from the edge, c) the “dead zone”

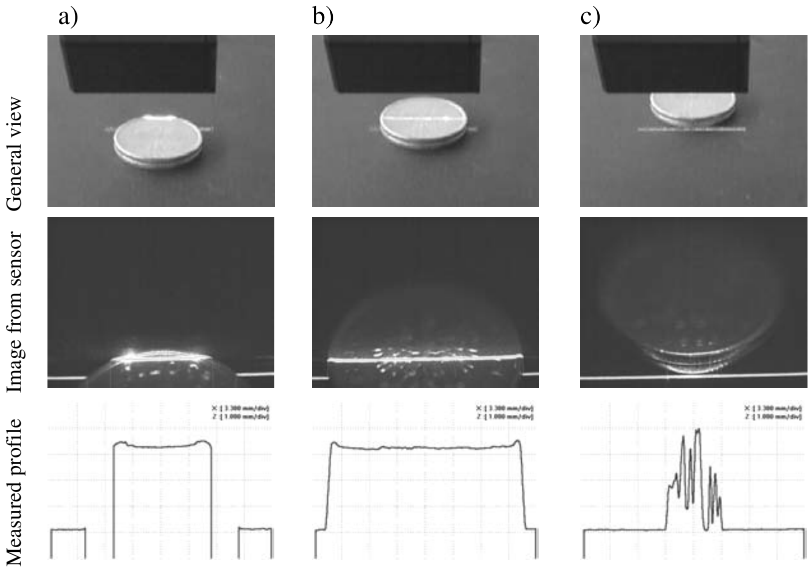

Fig. 3. Profiles recorded for different areas of scanning of the product [4]: a) interference in form of discontinuous profile, b) correct measurement, c) measurement in form of reflection from the highly reflective edge of the product

Interference in form of a discontinuous profile on the edges of the object are presented in Figure 3a. This interference may be caused both by the “shadow effect” and by the “dead zone effect” of the measurement head, depending on whether the interference is caused by the detection error or by the projection error. In the first case, the sensor "does not see" the lighted area; and, in the second case, the beam generated by the projector does not reach the observation area [4, 9]. In both cases, the measurement in those areas is not possible. Figure 3c presents the interference in the case of reflections from the highly reflective edge of the product.

3. The proposed method for multiple scanning

The use of a 2D measurement head for reconstruction of the surface geometry of the products of dimensions that do not exceed the measurement range of the sensor requires only one linear drive. In case of measurement in a wider range, the maintenance of high accuracy requires partial scanning of the surface and then the combination of the results in one consistent integrity. That process requires two linear drives in a cross arrangement (Fig. 4). This solution also allows the pre-positioning of the tested object related to the measurement head depending on the location to be scanned. The scanning method with use of cross-table in the X-Y arrangement is widely used in constructions of profilometers [4, 10, 11, 12].

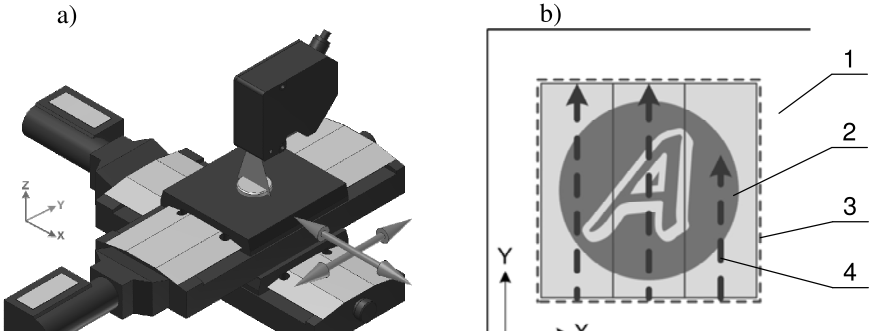

Fig. 4. The basic method of scanning using a cross-table X-Y: a) the concept of the structure of the profilometer [4], b) the scanning method: 1 – work area, 2 – tested object, 3 – scanning area, 4 – scanning trajectory

For minimisation of the occurring interferences of the measurement data, a method was developed for multiple scanning of the element for different angular positions. The solution consists in the introduction of an addition drive for rotating the tested object along the Z-axis (Fig. 5a). This allows additional scanning of the object with a different angle (Fig. 5b). As the result of the changes in the angular position in relation to the measurement head, the interferences of the measurement data occur in different areas of the surface of the element. This allows the reconstruction of the geometry of the surface based on the superposition of the results of the subsequent measurements after prior elimination of the interfered areas. Data from individual measurements mutually supplement each other, which allows the creation of a continuous surface [4, 13].

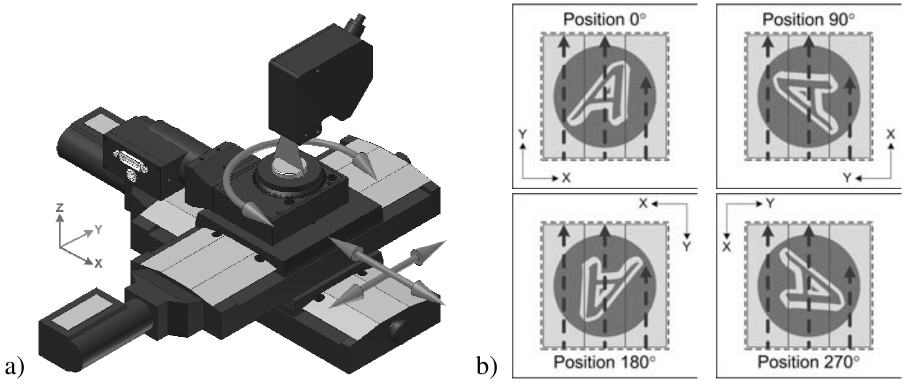

Fig. 5. The extended scanning method for the elimination of the measurement interferences: a) the concept of the structure of profilometer [4, 13], b) the scanning method for subsequent angular positions

The main advantage of the developed method is the significant reduction of occurring measurement interferences related to the "shadow effect" as well as to the reflections from highly reflective edges of the tested objects. The measurement cycle causes a four-fold extension of the duration of the measurement as related to singular scanning. It is a significant inconvenience, especially using the slow point-by-point scanning method. With the use of the 2D heads, the extension of the measurement time is not so significant.

4. The structure of profilometer

The developed construction of the profilometer (Fig. 6) is of a modular structure that includes three basic components: the granite chassis with a portal frame, X-Y table module with the turntable, and the measurement laser head module with the positioning system [4].

The modular structure allows further modification and extension of the functionality of the profilometer, for example, by application of another type of measurement head. For ensuring the rigidity and insensitivity to vibration, the chassis of the device constitutes a granite block that is supported by vibro-insulator pads. The portal frame, also made of granite, sits on the top of the block and ensures high rigidity, which allows precise positioning of the module of the measurement head in relation to the surface of the basis. The work surface of the granite block that holds the X-Y table module, and other surfaces of the block and the portal frame were ground and polished.

The flatness of the surface is under 2 μm and the deviation of perpendicularity of the surfaces does not exceed 2 μm.

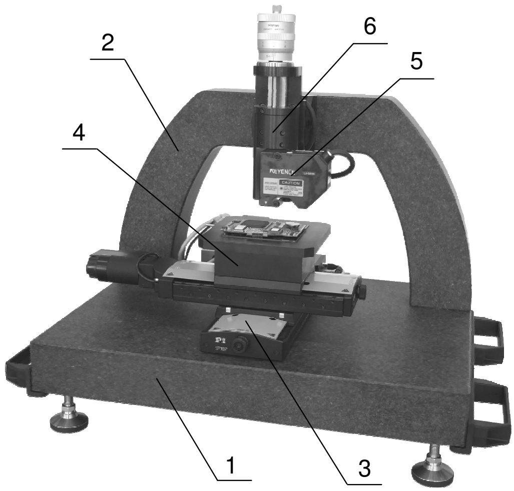

Fig. 6. The structure of the 3D laser profilometer: 1 – granite chassis, 2 – portal frame for measurement head, 3 – X-Y table module, 4 – turntable, 5 – measurement laser head, 6 – positioning system for measurement head

The positioning table is a module that allows linear scanning of the object in the X-Y plane and the rotation in the Z-axis. It consists of two linear drives and a turntable. The cross arrangement of two linear tables allows linear movement in the X-Y plane in the range of 100x100 mm. The turntable allows rotation of the working plate with tested sample of 0º to 360º. The applied precise drives were obtained from the Physik Instrumente (PI) GmbH & Co, and they use DC motors and are equipped with a feedback circuit using incremental encoders. The basic parameters of the selected drives are presented in Table 1 [4, 14].

Table 1. The basic parameters of the selected drives [4, 14]

Parameter	**Value**	
Movement type	Linear	Rotary
Range	100 mm	360º
Resolution	0.125 μm	32 μrad
Unidirectional repeatability	0.2 μm	50 μrad
Bidirectional repeatability	2 μm	–
Pitch of the screw / ratio of worm gear	0.5 mm	50:1
Top speed	15 mm/s	90º/s

The module of the measurement head consists of a laser head, a positioner, and the support, which is fixed into the granite portal frame. The precise positioning of the head is possible thanks to the positioner. The measurement head, through the adapter, is fixed to the carriage that, without backlash, mates with miniature T-shaped guide. The adapter is an exchangeable element that allows quick exchange of the laser triangular head and also allows the stability of the fixture. The basic parameters of the applied measurement head are presented in Table 2 [4, 5].

Table 2. The basic parameters of the applied 2D laser triangular head [4, 5]

Parameter	**Value**
Measurement range (Z axis)	20 mm
Measurement range (X axis)	20–25 mm
Resolution (Z axis)	1 µm
Resolution (X axis)	800 points (33 µm)
Repeatability (Z axis)	1 µm
Repeatability (X axis)	5 µm
Measurement nonlinearity (Z axis)	± 0.1% of the range

The module of the carriage and the micrometric head, thanks to manual regulation, allows vertical movement of the laser head in relation to the tested sample in the range of 0 to 50 mm.

5. The control-measurement system

The structure of the system consists of modules to perform particular functions (Fig. 7). The main element of the control system is an industrial PC computer. It communicates with particular devices with use of an USB digital interface. For scanning the surface, the measurement system is selected, which consists of the triangular laser head and the controller of the head. The control of linear and rotary movement stages is performed with use of three single-channel controllers combined in a network. Thanks to this solution, the communication task with all the controllers is performed with use of a single USB port [4]. The control-measurement system of the profilometer was placed in a desktop chassis (Fig. 8).

The software for controlling the operation of the profilometer was installed on the IPC computer. The software was developed in cooperation with Institute of Applied Optics in Warsaw. Depending on the performed functions, the software modules can be classified as follows [15]:

– Hardware control tasks (measurement head, positioning modules),

- The acquisition of measurement data (implementation of measurement algorithm),
- The analysis and processing of measurement data, and
- The presentation of the results.

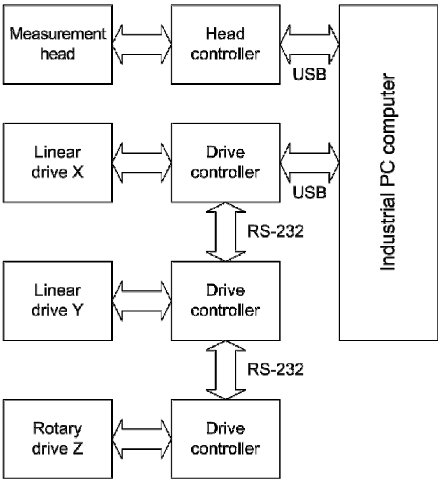

Fig. 7. General structure of the control system of the profilometer [4]

Fig. 8. The view of the chassis of the control system

Parameters of the laser head controller were set to minimise their influence on the output data. The values responsible for adding data from non-measureable points were limited to gain more control over the measurement data. The results from the points where the laser head was not able to perform measurements are simply replaced by the data measured at the same point with a different position of the positioning module. Based on the readouts from the device, the spatial position of each point is calculated. Data obtained from single scans are combined so that the cloud of measured points can be assigned to each of the four angular positions of the turntable. Data from the measurement devices are transformed to one measurement coordinate system with use of its rotation along the axis of the turntable. Next, the resampling operation is performed to achieve the set of data determined in the previously defined measurement grid. In each of the points of the grid, four values are obtained from different measurements with the laser head. The faulty values from the measurement head are rejected and the rest of the data is averaged [4, 15].

6. Sample results from the surface measurement

The experimental tests were performed. The surfaces of selected objects of different shapes, dimensions, and surface structure were scanned. The aim of the research was to experimentally test the proposed method of the elimination of the measurement interferences by multiple scanning of the surface for different angular positions. The results were recorded after each measurement cycle. Both end results and partial results from measurements were stored. The effects of the scanning of the surface are presented as a view from above. This method of data presentation allows simple analysis of the discontinuous areas, where the measurement was not possible. This article presents the results of the experimental research on the surface of a coin and printed circuit board. The coin is an example of an object of a highly reflective surface. The scanning area was 30 x 30 mm, and the scanning increment in both directions was set to 33 μm, which is equal to the measurement resolution of the laser head along the X-axis. Figure 9 presents the partial measurement results for particular angular positions of the turntable. On the images, the two main areas of the measurement interferences are marked, where one of them (A) is related to the "shadow effect" and the other (B) is caused by the additional reflections from the reflective edge of the coin. It should be noted that the surface of the coin was not prepared in any way for testing; in particular, it was not processed to eliminate the reflections.

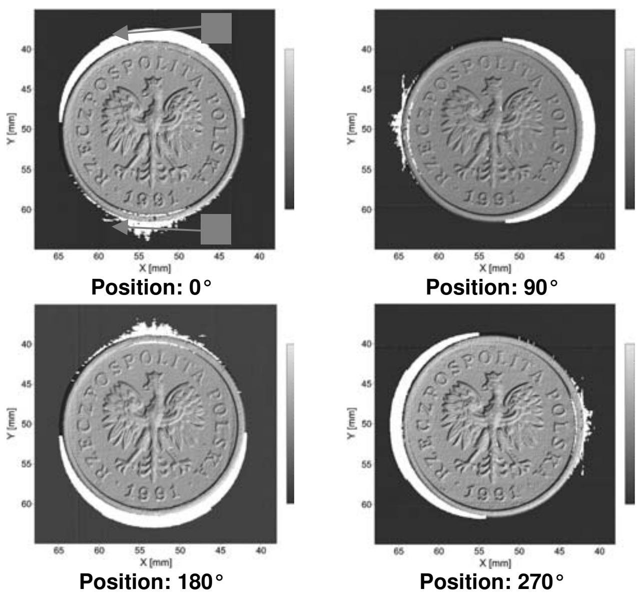

Fig. 9. The results of scanning a coin's surface for four angular positions of the turntable in relation to the measurement head

After the change of the angular position of the object in relation to the head, the interferences of received measurement data in subsequent measurements appear in different areas of the scanned surface. After the combination of partial results, it is possible to significantly reduce the discontinuity areas. The final result of the measurement of the surface, after the processing of data from four angular positions, is presented in Figure 10.

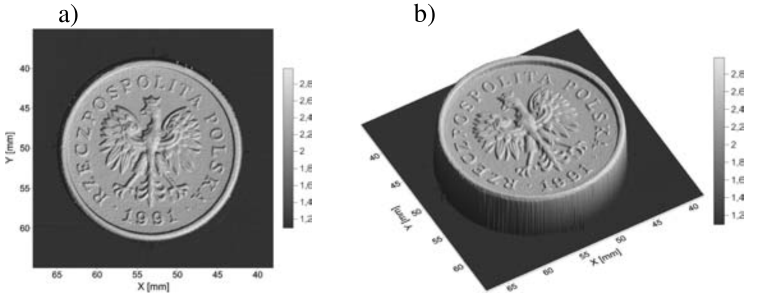

Fig. 10. The result of scanning a coin's surface combining four partial measurements: a) view from above, b) 3D view with interpolation of the non-measureable points

Tests were also performed on the surface of a printed circuit board (a SOM (System on Module) type minicomputer). Figure 11 presents the partial results of measurements for particular angular positions.

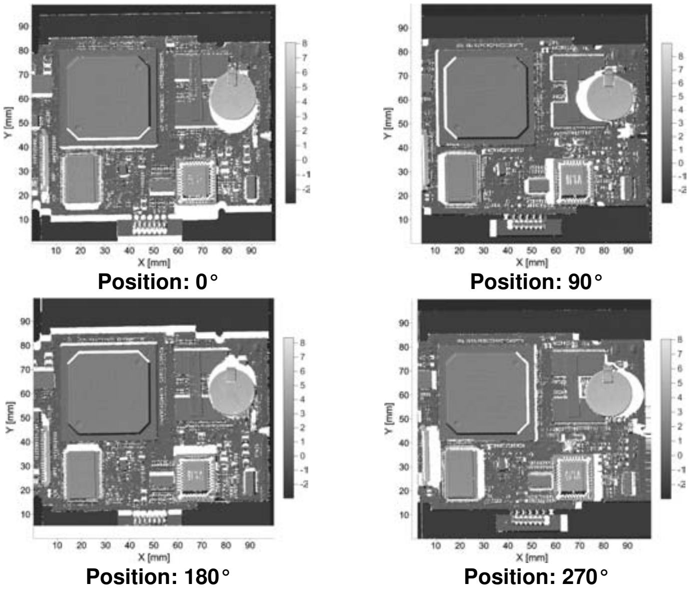

Fig. 11. The results of scanning of the surface of a printed circuit board for four positions

The object of the tests is made of materials characterised by a diverse structure of the surface. The scanning area was a full range of movement of X-Y linear drives that equals 100 mm, and the scanning increment was 50 µm. The result of the measurement of the surface of the electronic board, after the processing of four angular positions, is presented in Figure 12.

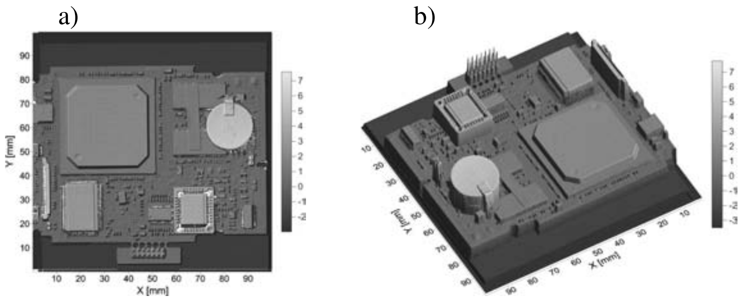

Fig. 12. The result of scanning of the SOM module surface combining four partial measurements: a) view from above, b) 3D view with interpolation of the non-measureable points

Despite the significant reduction of the discontinuity areas as a result of the combination of four partial measurements, there exist areas for which the profilometer was not able to perform the measurements. These areas might remain unchanged or might be eliminated by the interpolation method based on the neighbouring points [4, 15].

Summary

The result of the performed research and development is a laser profilometer with a 2D type measurement head that uses the author's method for the elimination of measurement interferences that are typical for the triangulation method. The general concept of the developed method consists in multiple scanning of the tested object for different angular positions and the analysis and combination of the received measurement results with use of proper filters to receive a continuous surface without interferences. After the preliminary research, it was decided that four partial measurements at multiplies of 90º are sufficient. As the result of changing the angular position of the object in relation to measurement head, the interferences of the received measured data in subsequent measurements appear in different areas of the scanned surface. It is then possible to reconstruct the shape of the surface based on the combination of results from subsequent measurement after prior elimination of the interfered areas. In case of measurement in a large range of dimensions, there additionally exists a scale problem where the measurement resolution is closely linked to the measurement range. The developed method allows scanning the neighbouring areas and then their combination into the consistent unity, which allows high-resolution measurements in the whole range of dimensions. The developed method and implemented algorithms were verified by experimental research, which consisted in scanning selected objects of different shapes, dimensions, and structures of the surface. The results of the research confirmed the correctness of the developed method and its usefulness for the reconstruction of the geometry of the surface in the Cartesian coordinate system. In the recorded results acquired from single scanning, a large number of non-measureable points was observed. The application of data processing based on four partial measurements allows significant reduction of the discontinuity areas.

The developed laser profilometer allows contactless measurement and reconstruction of the shape of the surface of the products, tests of material wear, damage of the surface, corrosion and erosion effects, and the quality inspection of the products.

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Wykorzystanie metody triangulacji laserowej 2D do odtwarzania geometrii powierzchni

Słowa kluczowe

Profilometria, metoda triangulacji laserowej typu 2D, efekt cienia, odtwarzanie geometrii powierzchni.

Streszczenie

W Zakładzie Mechatroniki Instytutu Technologii Eksploatacji – PIB w Radomiu został opracowany profilometr laserowy z głowicą triangulacyjną typu 2D. Zastosowana w urządzeniu bezstykowa metoda pomiaru odległości, z wykorzystaniem głowicy umożliwiającej skanowanie powierzchni jednocześnie w dwóch wymiarach, przyczynia się do zwiększenia szybkości procesu pomiarowego w porównaniu z alternatywnymi metodami punktowymi. Cechą charakterystyczną profilometru jest zaproponowana przez wykonawców oryginalna metoda pomiarowa, która ma na celu znaczącą redukcję ilości niemierzalnych punktów pojawiających się podczas pomiaru. Ogólna idea metody polega na wielokrotnym skanowaniu powierzchni badanego obiektu w wybranych kierunkach. Uzyskane wyniki pomiarów cząstkowych są następnie poddawane analizie i łączeniu w celu odtworzenia ciągłej powierzchni badanych wyrobów. Poprawność metody została zweryfikowana na podstawie badań eksperymentalnych dla wytypowanych wyrobów o zróżnicowanych kształtach.