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A METHOD OF SCREW THREAD MEASUREMENT USING A 3D VISION SYSTEM

Key words: screw thread, thread parameters, 3D image, triangulation.

Abstract: This paper presents a method allowing for the quality inspection of a screw thread directly on a production line. The parameter evaluation was performed on a surface partial image obtained using 3D laser triangulation. Three characteristic values are being measured for each element: minor pitch, major pitch, and pitch diameter. The paper contains an overview and discussion of methods commonly used for screw thread measurements. The non-tactile 3D imaging method that was selected for this task is fast enough to be used on every element which leaves the production line, and it is accurate enough to provide reliable data about the quality of the final product. Thread parameter assessment is based on a two-stage algorithm. The first step provides data about the overall placement of the elements, along with a rough estimate of the major diameter. The final values are then calculated using the least squares minimization method. This algorithm was verified using synthetic data representing an ideal thread contour, and then implemented for the analysis of the actual thread surface of a 3D image. Detailed algorithm execution time measurements were presented, along with our method to decrease computational costs for performing measurements on each screw thread.

Metoda pomiaru parametrów gwintu z wykorzystaniem technologii systemów wizyjnych 3D

Słowa kluczowe: gwint, parametry gwintu, obraz 3D, triangulacja.

Streszczenie: Artykuł przedstawia metodę kontroli jakości elementów gwintowanych możliwą do realizacji bezpośrednio na linii produkcyjnej. Pomiar parametrów został przeprowadzony, bazując na częściowym obrazie gwintu wykonanym przy pomocy triangulacji laserowej. Opisano metodę pozwalającą na wyznaczenie trzech charakterystycznych parametrów gwintu: średnicy wewnętrznej, średnicy wewnętrznej oraz skoku gwintu. W pracy przedstawiono przegląd metod powszechnie wykorzystywanych do pomiaru parametrów gwintu. Do realizacji zadania wybrano ostatecznie bezstykową metodę obrazowania 3D, charakteryzującą się szybkością wystarczającą, by można ją było zastosować dla każdego elementu opuszczającego linię produkcyjną oraz dokładnością pozwalającą skutecznie oszacować jakość produktów opuszczających linię produkcyjną. Opracowany algorytm wyznaczania parametrów gwintu składa się z dwóch etapów. W wyniku kroku pierwszego otrzymano zgrubną informację o położeniu oraz parametrach obrazowanego obiektu. Drugi krok pozwala na dokładne wyznaczenie szukanych parametrów z wykorzystaniem minimalizacji funkcji błędu. Algorytm został zweryfikowany z wykorzystaniem danych opisujących kontur idealny, a następnie wykorzystany do analizy danych pochodzących z rzeczywistego pomiaru. W artykule zaprezentowano dokładne dane dotyczące czasu wykonywania algorytmu wraz z metodą skrócenia czasu obliczeń dla każdego pojedynczego elementu.

Introduction

The process of inspecting threads in the "zero defects" system should be capable of checking all products leaving the production line, and should therefore be executed under industrial conditions with a capacity equal to that of the production line.

Threads are described with seven basic parameters that are subject to inspection. The process of quality assessment usually takes into account the pitch diameter, pitch, flank angle, major diameter, minor diameter, radius at root, and radius at crest [1].

The standard thread quality verification techniques are based on using thread gauges and specialized measuring techniques, such as a "three wires" method. These have been discussed in a broader way in the documents of the NPL [1] and the European Association of National Metrology Institutes [2]. However, methods of this type are known to have limitations. Gauges are vulnerable to wearing out, making periodic condition checks and the replacement of defective units necessary, which results in increased inspection costs. Assessment of the thread parameters with standard tactile methods is also dependent, to some extent, on the competencies of the operator conducting the inspection.

Another group of inspection methods is based on using coordinate measuring machines [3]. The algorithm developed by Kosarevsky and Latypov [4] with Hough transform allows the assessment of the parameters of a single screw thread profile, namely the thread pitch and flank angles. Measurements of this type require appropriate laboratory facilities and experienced operators, and cannot be conducted on the production line.

Optical measurement methods have been gaining popularity in recent times. More and more inspection tasks are executed using machine vision systems. A lot of work has been done recently, e.g., to inspect gear production [5] or the conditions of hoisting ropes [6]. Thread parameter assessment is not an exception here and is also a field of intensive research. Mutambi J. and Li-jun [7] have presented a method of determining the basic thread parameters on the basis of an image obtained with a CCD camera and a toolmaker's microscope. A statistical analysis method was used to determine the parameters: pitch, thread angle, pitch diameter, and major diameter. The achieved results were comparable with the traditional microscopic method.

He, Zhang, Du, and Cui [8] used a 2D image of the item in order to eliminate the impact of defects on the results of the measurement. Attention has also been paid to 3D methods and their possibilities in the context of measuring thread parameters. Robertson and Fisher [9] decided to reconstruct thread parameters on the basis of the cloud of points obtained with the triangulation method. In determination of thread axis, the authors assume that the thread may have any orientation. With relatively low expenditure of work, in real-life tasks, it is usually possible to ensure at least preliminary positioning of the measured object. Kosarevsky and Latypov [10] attempted to build a thread image with high-resolution computer tomography (CT). Such devices are usually used in medical applications to produce internal images of the human body. This approach offers significant possibilities in the case of internal threads, where measurements are particularly difficult. The CT scanner enables obtainment of a full image of the thread along the entire circumference of the element, allowing the parameters to be determined separately for each cross-section. The drawbacks of this solution are the time required for measurement with a CT scanner and the high cost of the instrument itself, which may be used only under laboratory conditions.

Each of the presented methods has certain limitations that make it difficult or exclude the possibility of using it in industrial measurement applications. In light of this, the development of a new method has been attempted that would allow comprehensive thread quality assessments to be made using a thread surface 3D image. The objective is to develop a solution that would allow measurements under industrial conditions directly on production lines. The method must be fast, effective in terms of calculation time, resistant to environmental interference, and eliminate the potential effects of an operator's actions on the results of the measurement. One important parameter of the selected method would be the time required to perform a full screw thread parameter assessment. Determining this time and optimizing the algorithm in terms of calculation cost were among the main objectives of the presented article.

1. Material and methods

The laser triangulation method (LTM) has been selected for the task of building a 3D image of the object. Similar results can also be obtained using optical micrometres. They consist of a laser line projector and a telecentric optical system, allowing for full 3D surface reconstruction. In our case, the main advantage of LTM is its flexibility. Elements with greatly varying geometrical dimensions could have been measured by simply replacing camera optics, but this cannot be done as easily with the kind of optical micrometres usually available as integrated systems. Moreover, since the field of view of a telecentric lens is always smaller than the diameter of the lens itself, their application field is limited.

Construction of the measuring station requires the selection of a camera-laser arrangement and optical system [11]. The camera-laser arrangement is an issue of particular importance in the discussed application. There are two possible approaches – the first allows for the creation of an image of thread plane development (Figure 1a). It is well suited for surface damage detection or other local parameter disturbances, since it contains data about an entire thread surface. The drawback is that each element has to be precisely rotated under a measurement system for an extended amount of time, which is not always an easily performed task. The second camera-laser arrangement allows one to register the set of height profiles with a linear shift of the threaded element (set on positioning elements against the fixed camera – laser system – Figure 1b). This configuration allows one to register only part of the thread surface lit by the laser beam. This increases throughput of inspection, but it does not allow measurement of the parameters of the object along its entire circumference. Theoretically, this approach may be used for a freely positioned thread. To shorten measurement time, the threaded element should be positioned with the axis of the thread roughly parallel to the plane of the laser beam. This setting allows for a full image of thread cuts to be built and reduces the occlusion effect. The 3D image building mechanism with the LTM method and the relationships between the field of view, camera–laser arrangement, and resolution have been discussed more extensively in the work of Sioma [11].

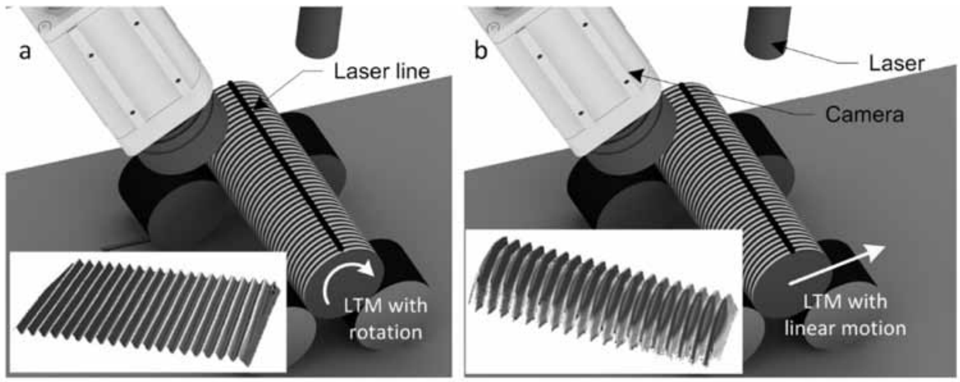

Fig. 1. 3D camera-laser arrangements: a – building the 3D image with rotation of the threaded element, b – building the 3D image with shifting the threaded element

Elements of various materials are threaded, from metals to ceramics and plastics. Since different surfaces feature different optical properties, each task execution method must be conducted individually. If the thread is made on a steel element, most of the laser light is subject to specular reflection. Plastics may feature a more diffuse reflection, with scattered light possible as well. The latter consists in light rays penetrating the material before leaving at some distance from the point of entrance. Such a surface, when lit with a laser, appears to shine in the area surrounding the point where the laser beam falls.

The element chosen as the subject of measurement in this paper is a threaded steel rod with a diameter of 40 mm. It has a surface with the diffuse reflection characteristic. For the selected element, the best results were obtained using a laser positioned perpendicular to the movement plane. The camera in the setup was positioned at a 50 degree angle with respect to the laser plane. The device selected for the task was a SICK Ranger camera that was specifically designed for 3D applications, featuring a 1536x512 grayscale image sensor and a profile rate of 35,000 per second. The resulting system resolution was 40um in all three axes. The values were calculated according to formulas presented in a work of Sioma [11]. The measurement setup was calibrated using the camera producer's proprietary calibration algorithm. The device selected for the measurement incorporates a pre-processing unit; hence, the output from the camera is not a raw image but a scaled depth map. Such an approach limits the amount of data that has to be sent to the main processing unit. The results presented below were obtained by using computer with Intel® Core™ i7 Q720 1.6 GHz processor, and 2x4GB DDR4 RAM memory. The laser used was Z-LASER ZM18B with a homogenous line profile and 635nm light wavelength.

The analysis of the data collected with laser triangulation is done in several steps. The first is to determine local extreme points of thread contour, and classifying them into two subsets that represent thread roots and crests. These points are selected from the 3D image with the image's initial analysis based on a numerical derivative of a profile. Preliminary processing indicates which points are valid for the purpose of the measurement of the selected thread parameter. For example, for the major diameter, a set of points is determined describing the external helix on the contour of the thread shown in Figure 2. In the next step, on the basis of the points that describe the thread contour, the subsets of the points are determined which describe the cylinder defining the major diameter, the sets of the points for the minor diameter, and the pitch diameter.

The measurement and verification of thread axis alignment, pitch, and minor and major diameters can be done using algorithms capable of calculating the parameters of the cylinders that describe the inspected diameters. This study used algorithms previously employed in the analysis of protein structures and in nuclear physics. The first of the above mentioned algorithms was discussed by Kahn [12], and it is based on the determination of two unit vectors and lying on the bisector of the angles defined by two triads of helix points that describe the thread contour (Figure 2a). Both unit vectors and are perpendicular to the axis of the helix; thus, their vector product results in a vector parallel to the axis of the helix.

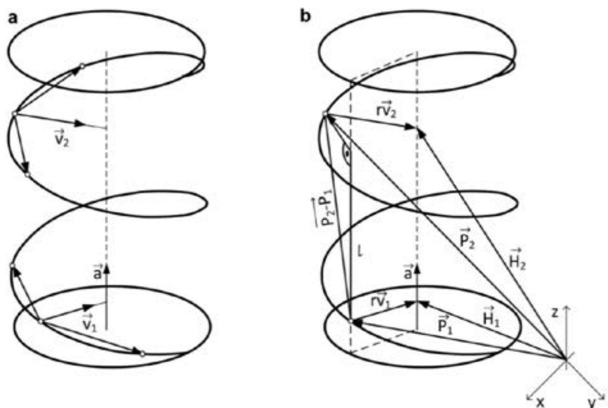

Fig. 2. The description of the vectors

The directional unit vector $\vec{a}$ describing the axis of the helix is determined as follows:

$$\vec{a} = \frac{\overrightarrow{v_1} \times \overrightarrow{v_2}}{|\overrightarrow{v_1} \times \overrightarrow{v_2}|} \tag{1}$$

Where $\left|\overrightarrow{v_1}\right| = 1$ and $\left|\overrightarrow{v_2}\right| = 1$. The distance l between the initial points of the unit vectors $\overrightarrow{v_1}$ and $\overrightarrow{v_2}$ measured along the axis of the helix is found from the dependence:

$$l = (\overrightarrow{P_2} - \overrightarrow{P_1}) \cdot \vec{a} \tag{2}$$

The initial radius value is determined as as follows:

$$r = \frac{\left|l\vec{a}\right|^2 - \left|\overrightarrow{P_2} - \overrightarrow{P_1}\right|^2}{2\left|\left(\overrightarrow{P_1} - \overrightarrow{P_2}\right) \cdot \overrightarrow{v_2}\right.} \tag{3}$$

where

- $\vec{P}_1$ – vector from the center of the coordinate system to the middle point of the first triad,
- $\overrightarrow{P_2}$ – vector from the center of the coordinate system to the middle point of the second triad,
- $\vec{a}$ – directional unit vector of the axis of the helix,
- $\overrightarrow{v_1}$ – unit vector determining the bisector of the angle of the first triad of the points,
- $\overrightarrow{v_2}$ – unit vector determining the bisector of the angle of the second triad of the points.

This method allows the determination of the approximate values of two parameters: the radius and the directional vector of the axis of the helix. These parameters are regarded as approximate due to using only 6 points for their determination. In the simplest variant, this method allows calculations to be made for four consecutive points that describe the helix. However, the accuracy of the determination of both parameters is dependent on the selection of the points and accuracy of their determination in the process of building the thread surface 3D image. During the study, it was discovered that two sets of three points each should be analysed and set apart at the largest distance possible as measured along the thread axis. The approximate parameters of the radius and of the directional vector of the thread axis are used as the input data for the final thread parameter estimation method.

The theoretical cylinder describing the major diameter is defined from the preliminary parameters. The cylinder is then compared with 2000 points that describe the helix that should be placed on its side surface. The measurement algorithm minimizes the sums of squares of the distances between the actual points that make up the helix and the approximate cylinder surface [13].

$$\Delta\left(r_{0x}, r_{0y}, r_{0z}, a_x, a_y, a_z\right) = \sum_{i=1}^{n}\left(d_i - r\right)^2 \tag{4}$$

where

- r_{0x}, r_{0y}, r_{0z} – the coordinates of the vector from the centre of the coordinate system to the theoretical axis of the cylinder, perpendicular to this axis,
- a_x, a_y, a_z – the coordinates of the directional unit vector $\vec{a}$ of the helix axis.

Minimization of the function above must be done with the assumptions that: $\overrightarrow{r_0} \cdot \vec{a} = 0$ and $\left|\vec{a}\right| = 1$. The vectors applied in any point of the helix and perpendicular to its axis, which define the distance of the point from the axis, are determined from the dependency:

$$\vec{d}_i = \vec{x}_i - \overrightarrow{r_0} - (\vec{x}_i \cdot \vec{a})\vec{a} \tag{5}$$

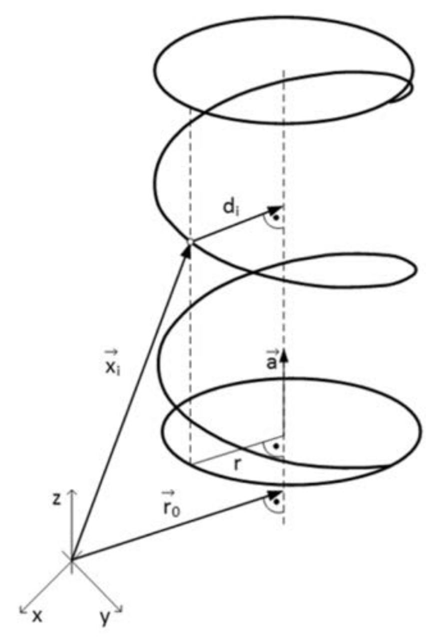

Fig. 3. A description of vector $\overrightarrow{d_i}$ defining the distance of each point on the helix axis

The minor diameter is done in the same manner with the use of the second data set. It should be noted that, apart from the averaged global parameters, information is also provided about the distribution of their values. This information allows the monitoring of the variability of the thread production process. On a production line, the duration of an inspection operation is extremely important, e.g., the duration of the measurement of the major diameter. It directly affects the production capacity or the percentage of the inspected products.

The article presents an analysis of the duration of the thread diameter measurement for four sets of initial values for the main algorithm. The following initial values have been assumed:

– The adopted constants of the coordinates of the vector describing the axis and the assumed fixed value of the radius,
– The approximate coordinates of the vector describing the axis from Formula 1 and the assumed fixed value of the radius,
– The constant coordinates of the vector describing the axis and the approximate value of the radius from Formula 3,
– The approximate coordinates of the vector describing the axis from Formula 1, and
– The approximate value of the radius from Formula 3.

2. Result and discussion

The thread diameter measurement algorithm was verified with the data generated using the following formulae:

$$x = a \cdot \cos(t),\ y = a \cdot \sin(t),\ z = k \cdot t \qquad (6)$$

A set of 2000 points were generated to represent a single thread circumference. The data set has been corrupted with noise with the normal distribution and the standard deviation equal to: 0.001; 0.005; 0.1; 0.2; 0.035; 0.05; 0.1 [mm]. For each of the prepared point sets, the diameter measurement was conducted and the corresponding algorithm execution time was determined. The measurements were repeated 100 times for each of the above deviation values to ensure that the obtained results are repeatable.

Figure 4 presents a comparative summary of algorithm execution time used to determine the major thread diameter. The average time value for each set of the repetitions is marked by the horizontal line. The first set of results describes the measurement execution time with the assumed constant coordinates of the axis vector and the assumed constant value of the radius for the consecutive values of the deviations. The second set of results describes the algorithm execution time for the preliminary determination of the vector describing the axis and the assumed constant value of the radius.

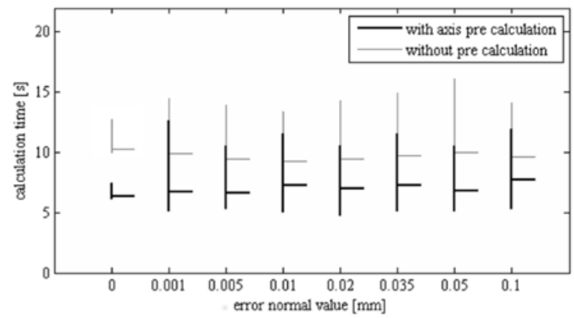

Fig. 4. The comparative analysis of algorithm execution time with the preliminary determination of the thread axis against the diameter measurement time with the assumed constant coordinates of the vector describing the axis and the value of the radius

Figure 5 presents the comparative summary of algorithm execution time used to determine the major diameter of the thread. The first set of the results describes measurement execution time with the assumed constant coordinates of the vector describing the axis and the assumed constant value of the radius for the consecutive values of the deviations. The second set of the results describes the execution algorithm time with the assumed constant coordinates of the axis vector and the preliminary determination of the radius.

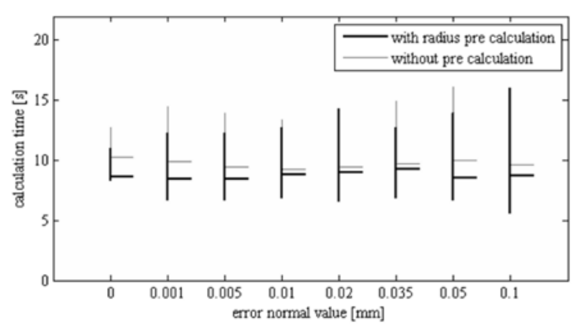

Fig. 5. The comparative analysis of algorithm execution time with the preliminary determination of the thread radius against the time of measurement of the diameter with the assumed constant coordinates of the vector describing the axis and the value of the radius

The comparative summary of algorithm execution time used to determine the major thread diameter with preliminary determination of the coordinates of the axis vector and the value of the helix radius is presented in Figure 6. The first set of the results describes the measurement execution time with the assumed constant coordinates of the vector describing the axis and the assumed constant value of the radius for the consecutive values of the deviations. The second set of the results describes the algorithm execution time with the preliminarily determined coordinates of the axis vector and the preliminarily determined radius.

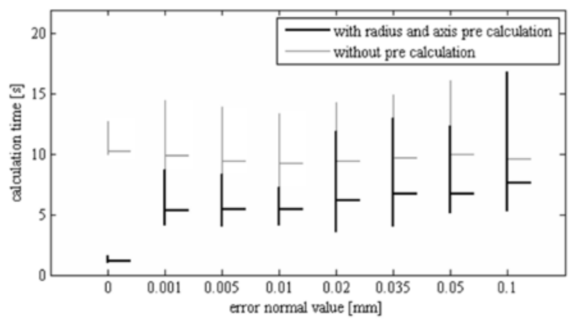

Fig. 6. The comparative analysis of algorithm execution time with the preliminary determination of the thread radius and axis against the time of measurement of the diameter with the assumed constant coordinates of the vector describing the axis and the value of the radius

The averaged values of algorithm execution time for various initial conditions and the diameter measurement time reductions are presented in Table 1. The table summarises the algorithm execution time with the pre-calculation of the helix radius, the pre-calculation of the thread axis, the simultaneous pre-calculation of the radius, and axis against the assumed constant coordinates of the axis vector, and the radius value.

After confirming algorithm performance on generated data, it was executed on data from real measurements. The standard deviation for the height measurement of the points that make up the thread area depends on: the camera-laser arrangement, the material of the thread, the geometric structure of the thread surface, the power of the laser lighting system, and the parameters of the optical system. In order to estimate the actual value of the deviation for the measurement of the height, experimental tests were conducted. These consisted of one thousand measurements of the same profile of the element with laser power controlled to the range from 10 to 100% of the rated power of the 35[mW] laser. For power exceeding 60% of the rated power and for the adopted 3D camera-laser arrangement, the lowest standard deviation for steel and aluminium with a value of 2 [µm] was obtained.

Table 1. The time value of shortening the algorithm execution time for various initial parameters

Error normal deviation [mm]		0.001	0.005	0.01	0.02	0.035	0.1	0.2
Execution time[s] for pre calculated value of:	–	10.3	9.89	9.46	9.29	9.47	9.71	9.97
	radius	8.61	8.48	8.45	8.84	9.02	9.26	8.58
	axis	6.34	6.71	6.60	7.26	6.96	7.22	6.84
	both	1.14	5.37	4.45	5.47	6.19	6.70	6.68

Table 2. The shortening the algorithm execution time for various initial parameters

Error normal deviation [mm]		0.001	0.005	0.01	0.02	0.035	0.1	0.2
Time reduction [%]	radius	16	14	11	5	5	5	14
	axis	38	32	30	22	27	26	31
	both	89	44	39	37	32	31	32

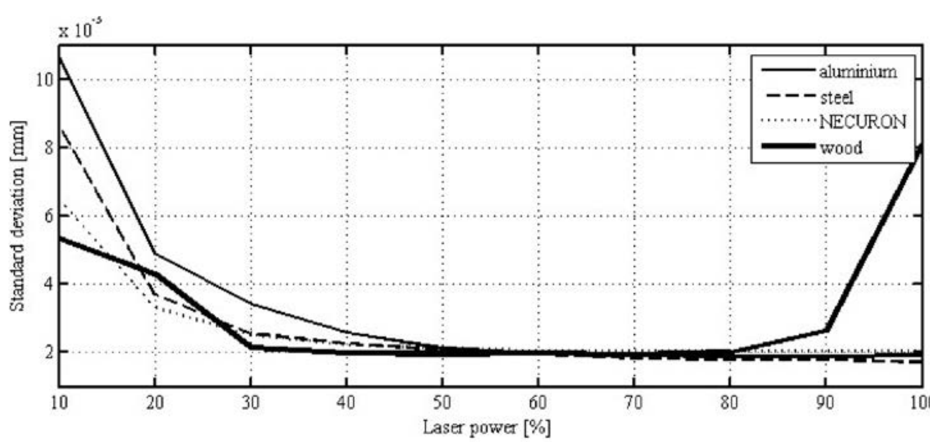

Fig. 7. The analysis of the standard deviation for the measurement of height of the points of the thread surface for the 35 mW laser

The above mentioned power value of the laser was used in the process of building the 3D image of the thread surface. The points that describe the visible part of the thread surface were used in the algorithm for the measurement of the thread diameter, taking into consideration the preliminary determination of the thread axis and radius. The preliminary analysis allows the determination of the characteristic points that represent the location of the roots and crests of the thread that describe its contour. In the next step, according to the presented algorithm, the preliminary location of the axis and the minor and major diameters were determined. The cloud of 2000 points representing the thread crests was used as the input data for the main algorithm to determine the location of the axis and its radius. This operation was then repeated for the cloud representing the thread depths. In both cases, the duration of the execution of the calculation was about 10 seconds. The following figure presents the cloud of the points and the cylinder with the parameters determined with the algorithms described in the article.

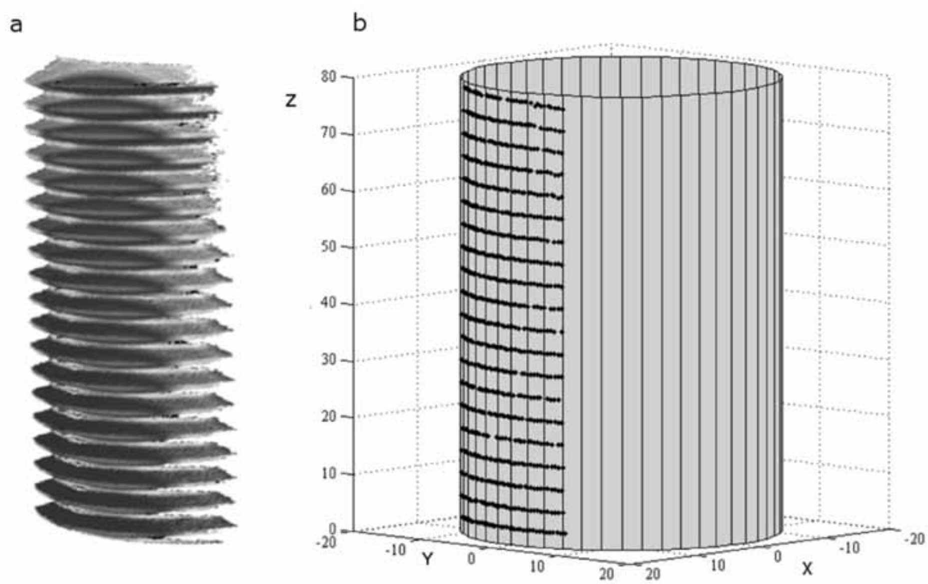

Fig. 8. Presentation of the results obtained on the basis of the analysis of the 3D image points

Conclusion

The LTM was used in this study for the acquisition of the 3D image of a screw thread. Two possible arrangements of the measuring station were proposed for the element executing the rotation around its own axis or the translatory motion. The first method may be successfully used in the case of threads whose production is related to putting the element into rotating motion. The shift of the thread against the camera and the laser is used in the second method. 3D scanning with triangulation takes considerably less time than in the case of the methods based on CMMs or a CT scan. The LTM combined with the algorithm of the two-stage determination of the thread parameters presented in the article allows a significant shortening of the required calculation time. Apart from the determined global parameters, i.e. minor, pitch, and major diameters, information about the distribution of their values is also obtained. This information allows the monitoring of the variability of the parameters of execution of the production process of the thread. In thread manufacturing, this information may be used in the process of intermediate assessments of wear on the tools used. In industry, inspection time is extremely important. The operation of inspection should be executed within a time that does not directly affect production capacity. The results presented prove that the selected method can be used to control production quality directly on a production line where throughput does not exceed 360 pieces per hour. This may be insufficient for some high throughput processes, but further improvements can be made using high performance computing hardware and parallel data processing. However, these topics are beyond the scope of this paper. The main advantage of the presented method is that it can be used without the need for the actions of an operator, which limits the potential impact of human error on the results. The presented method's resistance to environmental interference is largely dependent on the system's design in any particular application. Machine vision systems have proved to be a reliable method of quality control in many demanding environments.

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