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AUTOMATED SYSTEM FOR CONTROLLING SURFACE ROUGHNESS PARAMETERS USING LASER TRIANGULATION

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Abstract. *The article discusses the development of an automated system for controlling the surface roughness parameters of parts, integrated directly into the machining process on CNC machines. The relevance of the study is due to the increasing requirements for the quality of surfaces that determine the operational characteristics of products, in particular wear resistance, tightness and strength of joints. The object of the study is the process of non-contact measurement of the surface microprofile by the laser triangulation method. The paper proposes a method for determining the microrelief parameters based on the analysis of the laser spot displacement on the CMOS matrix. To increase the accuracy, an algorithm for subpixel determination of the signal energy center and digital filtering using a Butterworth filter are used, which allows minimizing the impact of noise, vibrations and production interference. The results obtained confirm the effectiveness of the proposed approach and allow reducing the percentage of defects by 12–15%. The proposed system corresponds to the concept of Industry 4.0 and contributes to increasing the level of production automation.*

Keywords: *roughness parameter control; laser triangulation; non-contact measurements; production automation; CMOS matrix; signal filtering.*

1. Introduction

The modern development of mechanical engineering and instrument-making is characterized by a transition to a high level of automation of production processes, which involves minimizing operator participation and ensuring stable product quality. In these conditions, control of surface roughness parameters of parts becomes of particular importance [1].

Surface microgeometry directly affects the operational properties of products, including wear resistance, joint strength, friction and durability. Ensuring specified roughness parameters is an important component of the technological process of processing.

At the same time, traditional approaches to surface quality control do not fully meet the requirements of modern production. This necessitates the development of new methods and measuring tools that can be integrated directly into the processing process.

The paper considers an approach to automated control of roughness parameters based on laser triangulation, which allows for non-contact measurement of the microprofile in real time.

2. Problem statement

Ensuring stable parameters of the surface roughness of parts during mechanical processing remains a difficult scientific and technical task, especially in automated production. The main requirement is the ability to carry out control directly during processing without stopping the technological process [2].

Existing contact methods are characterized by limited speed and are not suitable for use in real time. Non-contact optical systems, although they provide high accuracy, often turn out to be insufficiently resistant to the influence of production factors, such as vibrations, noise and pollution.

In this regard, the task of developing a control method that combines high speed, sufficient accuracy and the ability to integrate into automated control systems is relevant. Of particular importance is increasing the reliability of determining microprofile parameters by improving signal processing algorithms and reducing the impact of measurement errors.

3. Literature review

Methods for controlling surface roughness parameters are conventionally divided into contact and non-contact. Contact methods, in particular profilometry, provide high measurement accuracy, but their application is limited by low productivity and complexity of use in automated production [3].

Among non-contact approaches, confocal and interferometric methods have become widely used. They allow achieving high resolution, but are characterized by complexity of implementation and increased sensitivity to external influences [4].

The laser triangulation method is considered an effective alternative, since it provides a compromise between accuracy and speed. Its application in industrial conditions is promising due to the relative simplicity of implementation and the possibility of integration into automated systems [5].

At the same time, an analysis of literary sources shows that the issue of increasing measurement accuracy and noise immunity of such systems in real production conditions remains insufficiently studied.

4. Materials and Methods

The functioning of the developed automated system is based on the principle of active optical triangulation, which is based on solving the geometric parameters of the triangle formed by the radiation source, the investigated surface and the receiving optical system. Unlike passive methods, this technology involves active probing of the microprofile with a narrowly focused laser beam. The laser diode projects a light spot onto the surface of the part, and the scattered (diffuse) radiation is collected by a lens and focused on a photosensitive CMOS matrix located at a certain angle to the radiation axis. The optical diagram of the measuring module based on laser triangulation is presented in fig. 1.

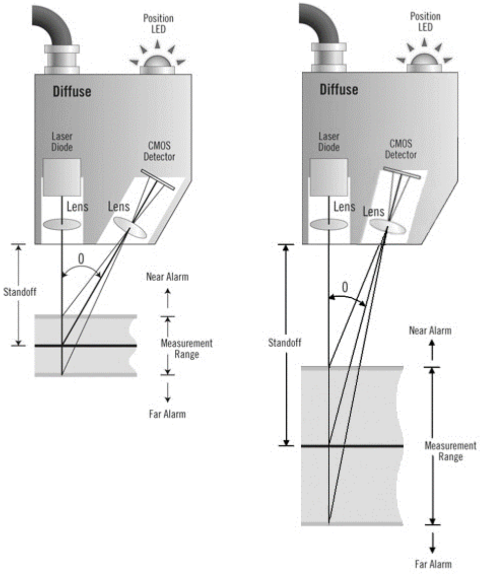

Figure 1 – Optical scheme and geometric model of the laser triangulation method

The fundamental task of the mathematical apparatus of the system is to convert the displacement of the light spot on the plane of the photodetector into a real change in the height of the microrelief. When the surface of the part has a protrusion or a depression, the point of incidence of the laser beam is shifted along its axis, which leads to a corresponding shift of the image of this point on the matrix. The mathematical dependence describing this process is derived from the trigonometric ratios of the optical scheme:

$$\Delta z = \frac{\Delta x \cdot L}{f \cdot \sin\theta + \Delta x \cdot \cos\theta}, \tag{1}$$

Where Δz – the desired change in the height of the microprofile (vertical deviation), which determines the amplitude parameters of the roughness, mm; Δx – the physical displacement of the energy center of the light spot on the CMOS sensor plane relative to the base point, mm; L – the working distance from the main optical plane of the lens to the zero measurement line, which determines the range of the sensor operation, mm; f – is the effective focal length of the receiving lens system, which affects the magnification factor of the scheme, mm; θ – the triangulation angle, i.e. the angle between the optical axis of the laser emitter and the axis of the receiver, degrees.

Since the image of a laser spot on the matrix usually covers an area of several pixels, there is a problem of discretization, which limits the measurement accuracy to the physical size of the pixel. To overcome this barrier and achieve the nanometer resolution necessary for the analysis of finished surfaces, the system implements an algorithm for calculating the centroid (energy center) of the spot. This allows determining the position x_c with an accuracy that is 10–20 times greater than the physical pixel pitch:

$$x_c = \frac{\sum_{i=k}^{m} i \cdot I_i}{\sum_{i=k}^{m} I_i}, \tag{2}$$

Where x_c – the calculated coordinate of the spot center; i – the pixel index; I_i – the signal amplitude (light intensity) recorded by the pixel; k and m – the boundaries of the reading area. This approach minimizes the influence of digital noise and provides high linearity of measurements.

The minimum step of roughness change, which is able to record the optical path, determines the sensitivity threshold of the system. It directly depends on the geometric configuration of the sensor:

$$S_z = \frac{p \cdot L}{f \cdot \sin\theta}, \tag{3}$$

Where S_z – the theoretical limit of vertical resolution, μm; p – the physical size of the matrix pixel. From the analysis of the formula it follows that to increase the accuracy it is necessary to increase the triangulation angle θ or reduce the working distance L, which is taken into account when designing the measuring head for different types of machines.

Since the measurements are carried out "in-situ", the received signal contains components of low-frequency vibrations and waviness. To isolate the roughness parameters, a Butterworth filter is used, the transfer function of which has the form:

$$H(s) = \frac{1}{1 + \left(\frac{s}{\omega_c}\right)^n}, \tag{4}$$

After filtering the array of z_i values, the system calculates the arithmetic mean deviation Ra, which is the basic indicator of processing quality:

$$Ra = \frac{1}{n}\sum_{i=1}^{n} |z_i - \bar{z}|, \tag{5}$$

Where n – the number of measurement points; z_i – the current deviation; $\bar{z}$ – the average profile line. Additionally, to assess the metrological reliability in conditions of shop noise, the total error σ_z is calculated, which takes into account the instability of the beam incidence angle due to microvibrations of the machine tool (σ_θ):

$$\sigma_z = \sqrt{\left(\frac{\delta z}{\delta x}\right)^2 \cdot \sigma_x^2 + \left(\frac{\delta z}{\delta \theta}\right)^2 \cdot \sigma_\theta^2}\,. \tag{6}$$

This set of mathematical models allows the system not only to measure microgeometry with high accuracy, but also to adapt to the dynamic conditions of the industrial environment, ensuring the reliability of data for further control of the technological process.

The developed automated roughness control system is integrated into the overall control structure of the metal-cutting machine as an intelligent feedback node. The interaction between its components and information flows is presented in the structural and functional diagram in fig. 2, and the algorithm of its operation is presented in fig. 3.

The main source of primary information about the surface microprofile is the measuring head, which contains a laser emitter (pos. 1, fig. 2) and focusing optics. The optical signal reflected from the part is recorded by a high-speed CMOS matrix (pos. 2), where light energy is converted into an array of electric charges. The received primary signal passes through the pre-processing block (pos. 3), which includes an amplifier and a hardware module for subpixel localization of the spot centroid to increase the accuracy of reading coordinates.

Next, the digital data is fed to the central computing module (pos. 4), the key element of which is the digital Butterworth filter (pos. 5). In this block, signal separation is carried out: separation of the high-frequency component (actually roughness) from low-frequency vibrations and waviness. Further analysis of the parameters is performed in the statistical evaluation block (pos. 6), where the Ra and Rz indicators are calculated based on mathematical models.

In the comparison block (pos. 7), continuous quality monitoring is carried out based on data on the regulatory tolerance limits (pos. 8), which are set by the technological map. In case of detection of critical deviation of parameters, the system through the logical decision-making module (pos. 10) sends an emergency stop signal to the machine tool actuators (pos. 13), in particular to the feed and main motion drives.

In addition, the system provides an adaptive control loop. Information about the current processing modes (speed, feed) comes from the CNC block (pos. 11) according to the control program (pos. 12). This data, together with the calculated roughness, is processed in the tool condition prediction block (pos. 9).

After determining the level of wear of the cutting edge, the data is transmitted to the correction formation block (pos. 10), where commands are generated for the CNC (pos. 11) to change the processing parameters in real time. If the correction does not allow the roughness indicators to return to normal, the system initiates a tool replacement cycle. The CNC, receiving the appropriate signals, makes changes to the control commands that are sent to the actuators (pos. 13) to safely complete or interrupt the operation.

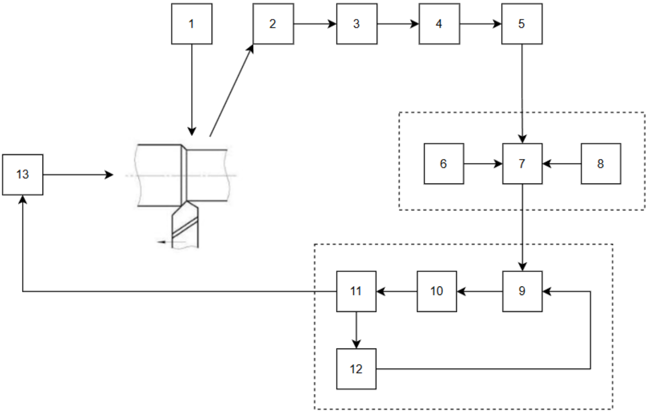

Figure 2 – Block diagram of an automated system for controlling surface roughness parameters of parts

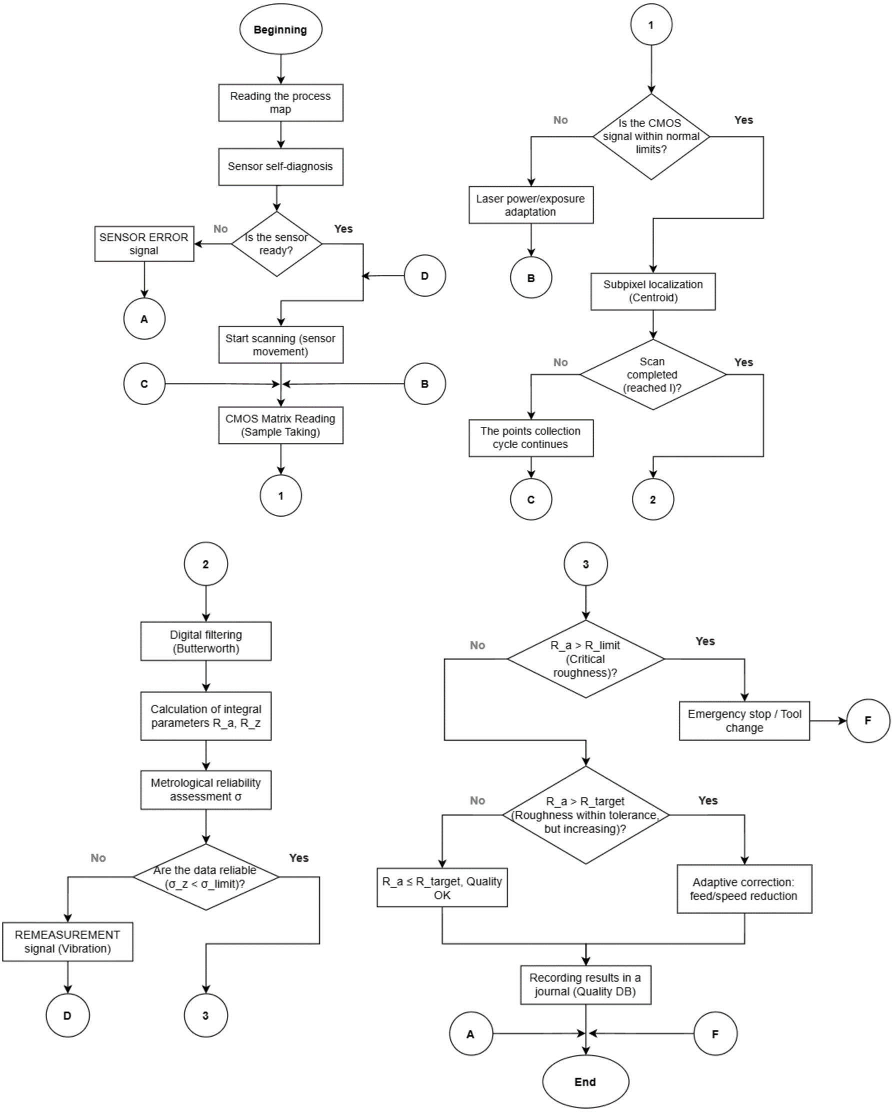

Figure 3 – Algorithm of functioning of the automated system for controlling the surface quality of parts

5. Experiments

The following parameters of the laser triangulation scheme were selected for the numerical experiment: $L = 100\,mm, f = 50\,mm, \theta = 45°$ ($\sin\theta = 0{,}7071;\ \cos\theta = 0{,}7071$); $\sigma_x = 0{,}00036\,mm$; $\sigma_\theta = 0{,}0001745$ rad

Partial derivative formulas:

1. By displacement: $\frac{\delta z}{\delta x} = \frac{L}{f \cdot \sin\theta} = \frac{100}{50 \cdot 0{,}7071} = 2{,}82843$
2. Around the corner: $\frac{\delta z}{\delta \theta} = \frac{\Delta x \cdot L \cdot \cos\theta}{f \cdot \sin^2\theta} = \frac{\Delta x \cdot 100 \cdot 0{,}7071}{50 \cdot 0{,}5} = \Delta x \cdot 2{,}8284$

Let $\Delta x_1 = 0{,}005\,mm$, then:

1. Height: $\Delta z_1 = \frac{0{,}005 \cdot 100}{50 \cdot 0{,}7071 + 0{,}005 \cdot 0{,}7071} = \frac{0{,}5}{35{,}3553 + 0{,}0035} = 0{,}01413\,mm$
2. Error according to the formula (6):

$$\sigma_{z_1} = \sqrt{(2{,}82843)^2 \cdot (0{,}00036)^2 + (0.005 \cdot 2{,}82843)^2 \cdot (0{,}0001745)^2}$$

$$\sigma_{z_1} = \sqrt{0{,}00000103675 + 0{,}00000000000607} \approx 1{,}0182\,\mu m$$

Let $\Delta x_2 = 0{,}015\,mm$, then:

1. Height: $\Delta z_2 = \frac{1{,}5}{35{,}3553 + 0{,}0106} = \frac{1{,}5}{35{,}3659} = 0{,}04241\,mm$
2. Error according to the formula (6):

$$\sigma_{z_2} = \sqrt{0{,}00000103675 + (0{,}015 \cdot 2{,}82843)^2 \cdot (0{,}0001745)^2}$$

$$\sigma_{z_2} = \sqrt{0{,}00000103675 + 0{,}0000000000546} \approx 1{,}0183\,\mu m$$

Let $\Delta x_3 = 0{,}040\,mm$, then:

1. Height: $\Delta z_3 = \frac{4}{35{,}3553 + 0{,}0282} = \frac{4}{35{,}3835} = 0{,}11305\,mm$
2. Error according to the formula (6):

$$\sigma_{z_3} = \sqrt{0{,}00000103675 + (0{,}040 \cdot 2{,}82843)^2 \cdot (0{,}0001745)^2}$$

$$\sigma_{z_3} = \sqrt{0{,}00000103675 + 0{,}0000000003886} \approx 1{,}0184\,\mu m$$

Let $\Delta x_4 = 0{,}085\,mm$, then:

1. Height: $\Delta z_4 = \frac{8{,}5}{35{,}3553 + 0{,}0601} = \frac{8{,}5}{35{,}4154} = 0{,}24001\ mm$
2. Error according to the formula (6):

$$\sigma_{z_4} = \sqrt{0{,}00000103675 + (0{,}085 \cdot 2{,}82843)^2 \cdot\ (0{,}0001745)^2}$$

$$\sigma_{z_4} = \sqrt{0{,}00000103675 + 0{,}0000000017551} \approx 1{,}0191\ \mu m$$

Based on the calculations, a data set was formed that reflects the dynamics of changes in the metrological characteristics of the system within the specified measurement range. The generalized results of the calculations of the microprofile height and the corresponding values of the mean square error are given below in table 1.

Table 1 – Simulation results

№	Δx, mm	Δz, mm	σ_z, μm	Recommended control system action
1	0,005	0,0141	1,0182	Continuation of processing
2	0,015	0,0424	1,0183	Continuation of processing
3	0,040	0,1131	1,0184	Feed reduction
4	0,085	0,2400	1,0191	Stop / Tool Correction

6. Results

Analysis of the simulation results allows us to formulate the logic of the automated system. At Δz values from 0,014 to 0,042 mm, the surface condition meets the requirements of finishing, and the measurement error remains stable, which allows us to continue the process without correction.

When the microprofile height increases to 0,113 mm, the system records the beginning of process destabilization: despite the fact that the total error increases only by fractions of a nanometer, a threefold increase in the measured value indicates initial tool wear or increased vibrations. In this case, the system initiates a feed reduction to stabilize quality. Reaching the critical mark of 0,240 mm by the Δz parameter indicates significant wear or breakage of the cutting edge, which is accompanied by the highest rate of error growth. In such a state, further processing will inevitably lead to a defect, so the intelligent algorithm issues a command to completely stop the equipment to replace the tool or introduce technical correction.

7. Discussion

The results of the study indicate the feasibility of using the laser triangulation method to implement non-contact control of surface roughness parameters in automated production.

The main advantage of the approach is the ability to combine sufficient measurement accuracy with high speed, which makes it suitable for use as part of process control systems. This opens up the possibility of transitioning from periodic to continuous control of the surface condition.

At the same time, the efficiency of the system is largely determined by the choice of optical circuit parameters and signal processing algorithms. In real production conditions, equipment vibrations and lighting instability can have an additional impact, which requires further improvement of filtering methods and error compensation.

Conclusions

Automation of non-contact control of surface microgeometry in real time is a key stage in the development of modern intelligent production. The introduction of "in-situ" laser diagnostics systems allows to radically increase the stability of technological processes and ensure guaranteed product quality in finishing operations. The use of progressive methods of digital filtering and subpixel processing of optical signals provides high metrological reliability of control of roughness parameters even under conditions of intense vibrations and dynamic interference inherent in the operation of metal-cutting equipment.

The integration of active control tools with the CNC architecture allows the system not only to record deviations, but also to promptly adjust processing parameters, minimizing the impact of tool wear and the human factor. This approach contributes to a significant reduction in production costs, optimization of equipment service life and increase in the overall energy efficiency of industrial complexes.

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АВТОМАТИЗОВАНА СИСТЕМА КОНТРОЛЮ ПАРАМЕТРІВ ШОРСТКОСТІ ПОВЕРХНІ ДЕТАЛЕЙ ЗА ДОПОМОГОЮ МЕТОДУ ЛАЗЕРНОЇ ТРІАНГУЛЯЦІЇ

Анотація. *У статті представлено розробку автоматизованої системи контролю параметрів шорсткості поверхні деталей, інтегрованої безпосередньо у виробничий цикл механічної обробки. Актуальність дослідження зумовлена зростанням вимог сучасної промисловості до експлуатаційних характеристик виробів, оскільки мікрогеометрія поверхні суттєво впливає на зносостійкість, герметичність і втомну міцність з'єднань. Показано, що традиційні методи контролю, зокрема контактне профілювання та використання хроматичних зондів, мають обмежену ефективність у виробничих умовах через чутливість до вібрацій, забруднення та значні витрати часу на вимірювання і повторне базування деталей. Об'єктом дослідження є процес безконтактного вимірювання мікропрофілю поверхні із застосуванням методу лазерної тріангуляції. Розкрито фізичні принципи формування триангуляційної схеми та наведено аналітичні залежності між зміщенням лазерної плями на CMOS-матриці й реальними параметрами висоти нерівностей поверхні. Запропонована структура системи охоплює повний цикл обробки даних: від первинної фільтрації оптичного шуму та компенсації похибок, спричинених розсіюванням світла, до обчислення стандартизованих параметрів шорсткості. Додатково обґрунтовано вибір параметрів оптичної схеми та чутливих елементів системи з урахуванням умов реального виробництва. Особливу увагу приділено алгоритмічному забезпеченню, реалізованому за принципом зворотного зв'язку. Розроблений алгоритм забезпечує не лише оцінювання відповідності параметрів шорсткості заданим вимогам, а й формування керуючих впливів для промислових контролерів з метою оперативної корекції режимів різання при зносі інструменту. Практичне значення роботи полягає у можливості створення замкнутих інтелектуальних систем контролю якості типу in-situ, що сприяє зниженню рівня браку на 12–15% і підвищенню рівня автоматизації машинобудівних та приладобудівних виробництв у межах концепції Індустрії 4.0.*

Ключові слова: *контроль параметрів шорсткості; безконтактні вимірювання; лазерна тріангуляція; CMOS-матриця; обробка сигналів; автоматизація виробництва.*