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AUTOMATISATION OF MULTI-PARAMETRIC QUALITY INSPECTION OF ROTARY SYMMETRICAL METAL ELEMENTS

Key words: production, manipulator, multi-parametric quality inspection, contactless measurement, zero fault.

Abstract: The article presents the concept of an optomechatronic module for automatic multi-parametric quality inspection of products. Laser techniques and optical inspection methods were selected for contactless measurements of several dozen parameters characterizing the product. Experimental studies have confirmed the effectiveness of the proposed measurement methods and have enabled the development of an integrated measurement system designed to work with a multi-axis manipulator feeding details from CNC machines. The aim of the described works was to develop an inspection system that will significantly increase the economic efficiency of production by eliminating defective products in line with the "zero fault" approach without disrupting the manufacturing process.

Automatyzacja wieloparametrycznej kontroli jakości osiowosymetrycznych wyrobów metalowych

Słowa kluczowe: produkcja, manipulator, wieloparametryczna kontrola jakości, pomiar bezkontaktowy, zero braków.

Streszczenie: W artykule zaprezentowano koncepcję optomechatronicznego modułu do automatycznej wieloparametrycznej kontroli jakości wyrobów. Do bezkontaktowych pomiarów kilkudziesięciu parametrów charakteryzujących wyrób wytypowano techniki laserowe oraz metody inspekcji wizyjnej. Przeprowadzone badania eksperymentalne potwierdziły skuteczność zaproponowanych metod pomiarowych oraz pozwoliły na opracowanie projektu zintegrowanego systemu pomiarowego, dedykowanego do współpracy z wieloosiowym manipulatorem dostarczającym detale z obrabiarek CNC. Celem realizowanych prac jest opracowanie systemu inspekcji, który zapewni istotne zwiększenie efektywności ekonomicznej produkcji dzięki eliminowaniu wyrobów wadliwych zgodnie z podejściem „zero braków" bez zakłócania procesu wytwarzania.

Introduction

Using automated inspection systems increases the efficiency and reliability of inspections. This is primarily due to the elimination of the human factor associated with lack of repetition, fatigue, subjectivity, and low efficiency [1]. The use of non-contact optical inspection methods, in many cases, allows for the replacement of statistical, selective inspection by on-line systems directly installed on production lines, without compromising performance [2–5]. Another possible solution is the construction of independent off-line devices, to which controlled details are supplied by batches by process operators [6]. In case where single measurement technique is possible and no complex manipulation of the details is required during the inspection process, such a solution will allow a high inspection rate. In more advanced systems requiring the use of various types of measuring techniques and the proper transportation of the product to the subsequent inspection zones, optimization of the design of the measuring module becomes a very important issue.

Under the agreement with Bartech Engineering Company, realizing the project "Compact system for automated CNC machine operation with optomechatronic product quality inspection" within the framework of Operation Program Intelligent Development 2014-2020, a module for automatic quality inspection of products was developed. The development of the concept of the inspection module was preceded by a detailed analysis of the end-user requirements. The basic requirement concerned the type of quality inspection carried out. According to the zero fault approach, the inspection is intended to cover all geometrical dimensions, including shape and position errors. The inspection should apply to 100% of the manufactured details (Figure 1) within the range defined in the technological guide.

The range of inspected details includes rotary symmetrical products with a diameter of up to 60 mm and lengths up to 140 mm with a mass not exceeding 0.8 kg. A technical drawing showing one type of a series of inspected details is shown in Figure 2.

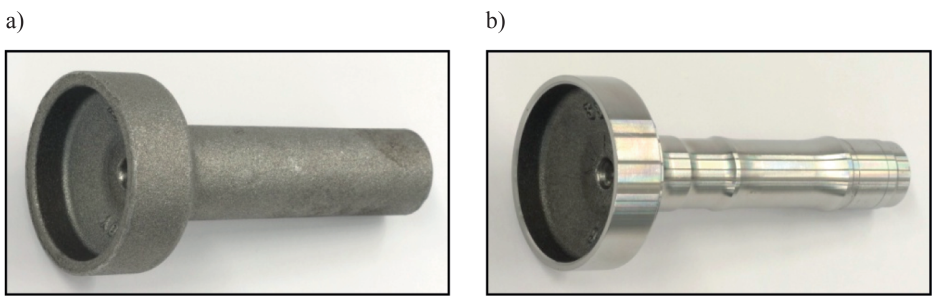


Fig. 1. The view of a sample detail: a) blank (forged), b) machined element

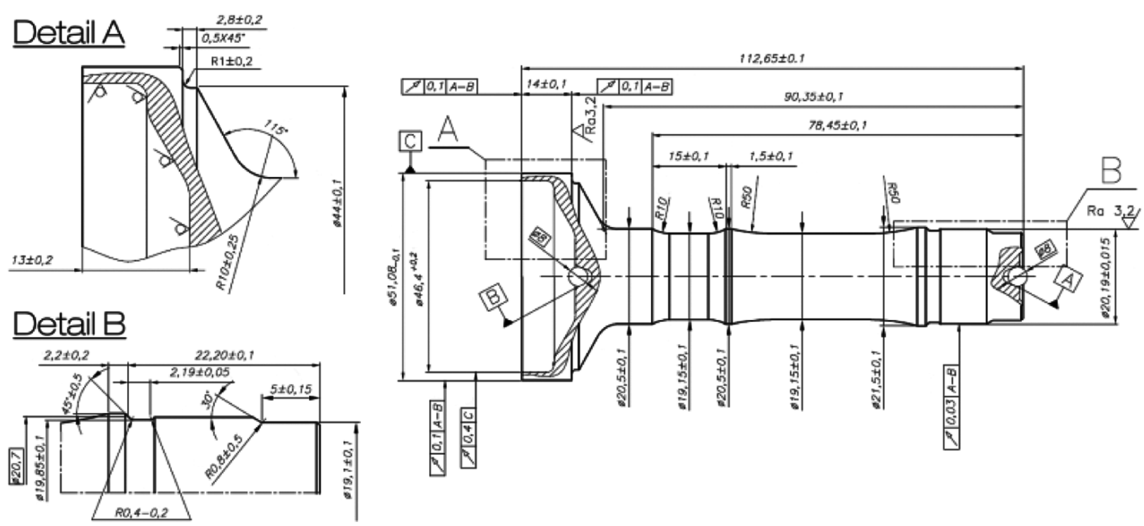


Fig. 2. Technical drawing of a sample detail subjected under inspection

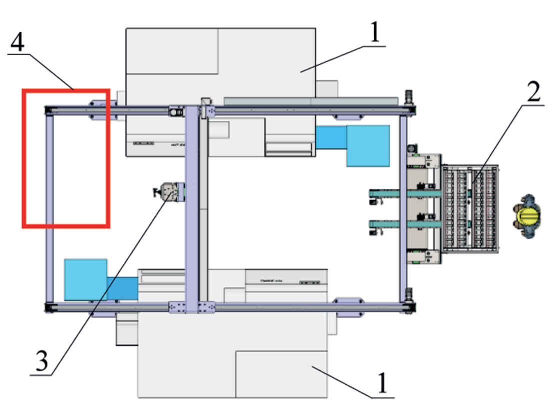


Fig. 3. The structure of the technological setup: 1 – CNC lathe, 2 – blank storage, 3 – portal manipulator, 4 – location of the quality inspection module

Another requirement was the minimum efficiency of the quality inspection process. Due to the planned use of a system for the handling of two CNC machines producing identical details, a maximum inspection time of 40 seconds was set. This time corresponds to half the actual processing time of the single least complicated part.

The immediate consequence of such a requirement is the need to locate the inspection module in the area of the existing technological setup (Fig. 3). It directly affects the maximum dimensions and service access to the components that make up the technological setup.

The following assumptions have been adopted in the developed concept:

– Inspected items will be delivered via a portal manipulator that supplies CNC lathes.

– Contactless laser techniques and optical inspection methods will be used in the inspection process.
– Prior to the measurements, the details will be subjected to a process of purification in the stream of compressed air to remove the remaining microparticles and droplets of the cooling liquid.
– Positively classified detail will be subjected to corrosion protection by immersion in a preservative liquid.

1. Selection of measurement techniques and experimental studies

For the measurement of geometric values, contact methods are widely used. The advantage of these methods is the very high accuracy and reproducibility of the measurement. However, they have some disadvantages, including the need for direct contact of the measuring tip with the surface to be analysed, low speed of movement, ease of damage of the measuring tip, and the possibility of damage to the surface of the tested products. For this reason, efforts have been made for a number of years to develop other methods of measuring geometric values, alternative to contact methods. The leading role is played by techniques that use light as a medium of information about measured magnitudes. This is possible thanks to the rapid development of optoelectronics and advances in microprocessor technology [7]. Optical methods are methods with potentially very high measurement speeds. Their main drawback is that the instruments based on them can generate faulty measurements due to the presence of dirt, metal particles, and machining fluids [8]. That is why it is important to prepare the surface properly before making any measurements.

The developed concept assumes the inspection of products using contactless optoelectronic measuring techniques in two stages:
– Measurements related to the inspection of the inner surface of the dome (performed after gripping the detail in the jaws of the manipulator); and,
– Measurements related to the inspection of the side surface, requiring the rotation or linear movement of the product (performed after the product is clamped in the cone gripper).

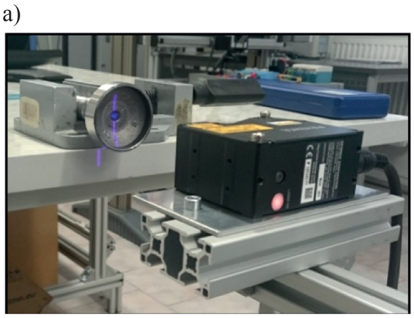
According to the assumptions, the gripping of the workpiece with the manipulator's jaws will be realized in the cylindrical part of the workpiece, outside the area of the dome, near the centre of mass of the workpiece. The visible surface of the dome makes it possible to carry out measurements of this area without depositing the part for inspection. The dome inspection includes depth measurements, internal diameter measurements, and radial eccentricity measurements.

Measurements on the inner surface of the dome will be made using two measuring techniques:
– A laser triangulation method (2D measurement head), and
– An optical method (digital camera with telecentric lens).

Both measuring systems are shifted relative to one another, and the geometry inspection will be carried out sequentially while moving the part between successive measurement subsystems.

For measuring the depth of the dome, the concept of a measuring system using a non-contact 2D laser triangulation method was developed. In this measurement method, the laser projects on the surface of the object a line formed by the laser beam passing through the cylindrical lens system. The light reflected from the surface of the object passes through the lens system and is projected onto the photosensitive matrix placed at an angle to the laser source. Changing the distance of the illuminated area from the measuring head causes the images of these areas to change on the photosensitive matrix [7, 9]. The results of a single measurement are the coordinates of the points that belong to the laser line projected on the surface of the object, creating an image of a contour (2D profile) of the surface. Based on the 2D profile obtained, it is possible to determine the depth of the dome. A measuring system, consisting of a laser measuring head and a controller allowing on-line analysis of registered 2D profiles was selected. Experimental studies were performed (Fig. 4).

a)



b)

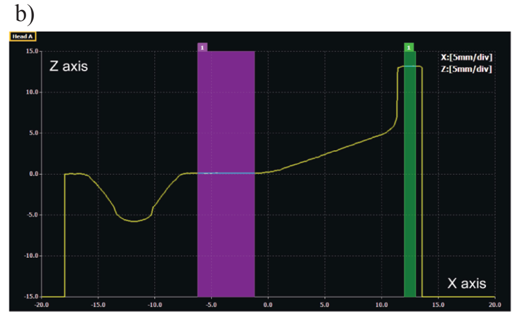


Fig. 4. Experimental tests of the depth measurement system: a) Photo of the measurementstand, b) Sample measured 2D profile (yellow) with marked measuring windows (purple and green) with respect to which the height difference is determined

The measuring range in the X-axis (along the laser line) of the selected laser head is smaller than the diameter of the canopy, so measurements should be made for two positions of the controlled product. The use of a laser head with a larger measuring range was not considered, because this would reduce the accuracy of measurement in both the X- and Z-axes.

On the basis of the measured profile (Fig. 4b), the average height value of the two selected measuring windows is determined, and a height difference corresponding to the depth of the dome is measured. Measurements are performed automatically in the laser head controller, and the measured value of depth is sent to the computer.

For the measurement of the inner diameter and the measurement of the radial eccentricity of the dome, a measurement method was developed using a digital camera with a telecentric lens. The telecentric lens, in contrast to the standard (entocentric) lens, provides approximately constant magnification in the operating range of the observation. It also eliminates errors from the perspective and is characterized by very low optical distortion [10, 11]. These features of the telecentric lens are particularly important in applications requiring precise geometric measurements. The necessity to meet the condition of the parallelism of light rays to the optical axis of the lens causes the front lens to have a diameter greater than the diameter of the required field of vision. Consequently, the size and weight of the telecentric lens are much larger than of the standard lens. Figure 5 presents an experimental stand for measurements performed on the inner surface of the dome using an optical method. The research stand is composed of elements available in the Department of Mechatronics and is not optimized for the measurement of the selected products. For the lighting of the observation area, a LED ring light located in the optical axis of the lens was used. The measurement system used requires calibration by means of a standardised known pattern. It is also necessary to provide the required space above the object to be tested, which consists of a minimum lens observation distance, telecentric lens length, and camera size.

a) b)

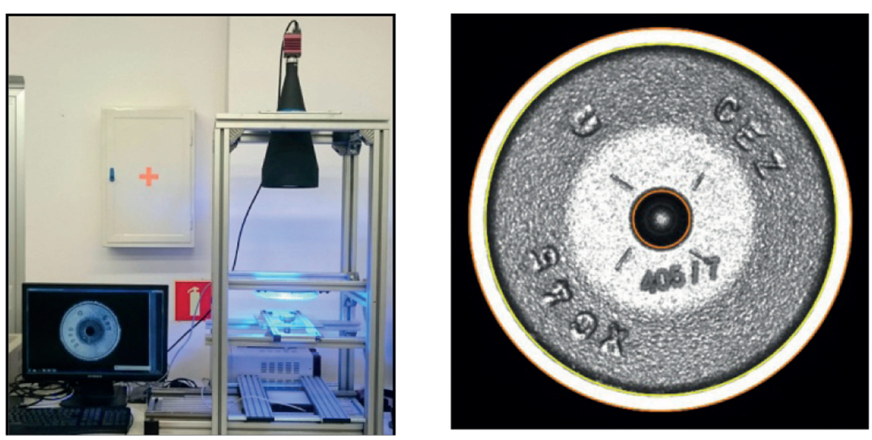


Fig. 5. Inspection of the inner surface of the dome by means of an optical method: a) illustrative view of the experimental stand, b) example of a recorded image

Based on the developed image analysis algorithms, the geometrical centre of the dome is determined in the first step, followed by the inner diameter and the radial eccentricity measurement. Measurements are performed by a computer using image processing and analysis software.

After the measurements have been made on the surface of the dome, the manipulator will move the detail to the next measurement stand, where the product will be clamped in the cone gripper. The planned measurement range includes the following: the measurement of diameters, radiuses, distances, depths, phases, angles, and radial and axial eccentricity. Measurements will be made using two measuring instruments: an optical micrometre and a 2D laser triangulation head (Figure 6).

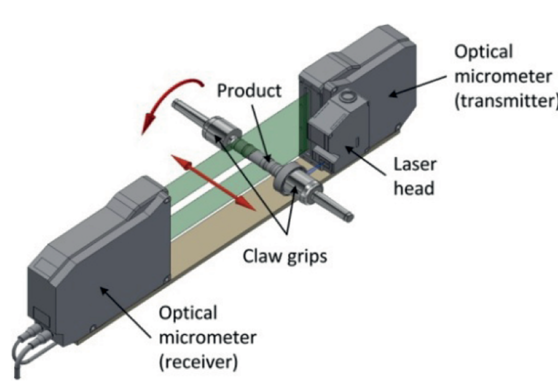


Fig. 6. Optomechatronic module concept for inspecting the side surface of details

The optical micrometre consists of a light-emitting element (transmitter) and a receiver. The light-generating element produces a parallel, continuous light curtain that falls on the lens receiver and the photosensitive array. The tested product, placed between the transmitter and the receiver, interrupts the light curtain. On this basis, the receiver measures the contours created by the shadow created by the product. For axial and radial eccentricity measurements, the detail mounted in the cone grippers will be rotated. Additionally, for the precise positioning of the workpiece, a linear travel with position control is used with a linear encoder.

The measurements of external dimensions, the top and bottom edge positions, and the centre of the workpiece can be measured using an optical micrometre. These values are determined directly by the controller of the measuring system. One can additionally determine the radial eccentricity values by measuring the changes in the position of the edge (bottom or top) during rotation. By introducing linear motion with no rotation, it is possible to produce a table showing the position of the part relative to the measuring system (based on the encoder data) and correlated with the position of the edge of the detail (optical micrometre). Based on that acquired cloud of points, once the data has been transferred to the computer, it is possible to recreate the contour of the workpiece and then to determine the required geometric dimensions in the form of radiuses, distances, phases, and angles. The structure of the measurement system, which consists of the optical micrometre head and the controller, allows the recording and analysis of measurement data (Fig. 7).

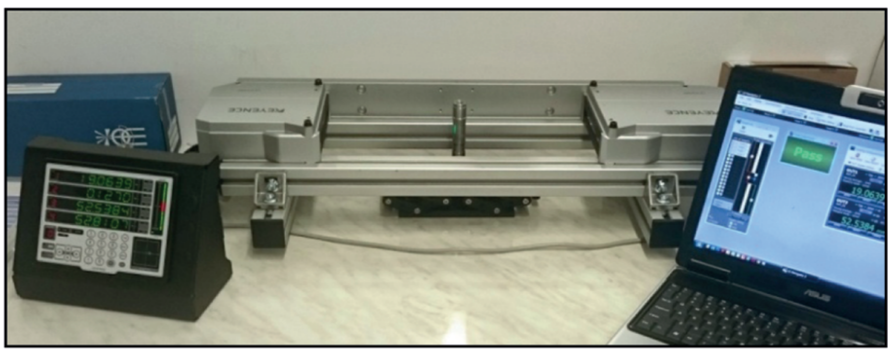


Fig. 7. The test stand with an optical micrometre

On the stand, the measurements were made in stationary conditions, without the rotation of the workpiece. The position of the workpiece relative to the measuring head was changed with the manual positioner. Sample measurements obtained with an optical micrometre are shown in Figure 8. As described above, the optical micrometre allows measurements of external dimensions (diameters for rotary symmetrical products, graphical representation No. 1 in Figure 8b), measurements of the centre position of the product relative to the reference position in the middle of the measuring range (No. 2), measurements of the upper edge of the workpiece relative to the beginning of the measuring range (No. 3) and, respectively, measurements of the lower edge relative to the end of the measuring range (No. 4). In order to inspect the geometric parameters of the details, the external diameter and the edge position measurement are used.

a) b)

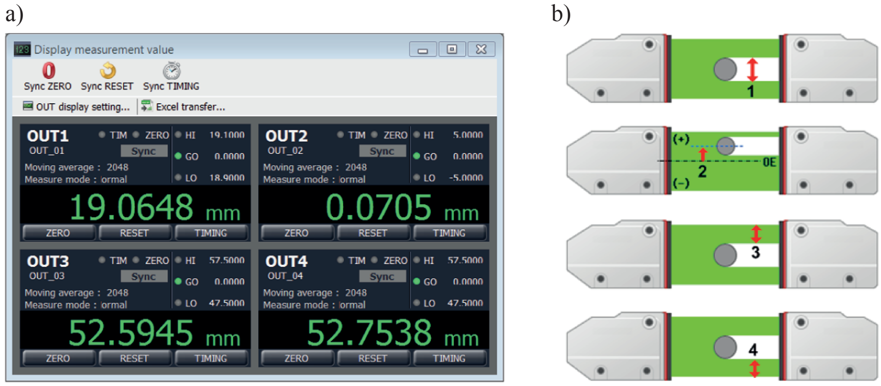


Fig. 8. Examples of measurement results using an optical micrometre: a) measured values: OUT1 – measurement of the outside diameter, OUT2 – measurement of the middle position, OUT3 – measurement of the upper edge, OUT4 – measurement of the lower edge, b) graphic representation of the data

The micrometre has an interface for the direct connection of the encoder and triggering the recording of measured data in fixed steps. Recorded measurement data can then be sent to a PC for further analysis.

Most measurements made on the side surface of the workpiece will be made using an optical micrometre. Determination of axial eccentricity requires the use of an additional measuring system. For this purpose, a 2D laser head is used to measure the position of the edge of the dome during rotation. In order to confirm the correctness of the proposed measurement method, tests were carried out on an experimental stand (Fig. 9). The rotary actuator with a handle is a part of the 3D-R confocal profilemetre developed at ITeE-PIB [12]. In experimental studies, the detail was not clamped in the cone gripper (as planned in the target solution) but one-sidedly in the self-centring triple bracket.

The study was conducted using two types of measuring heads that differ in measuring ranges. The laser scanning head No. 1 covered the entire width of the canopy, allowing simultaneous measurements of the position of the two edges during the test element. An example of the measurement result using No. 1 head is shown in Figure 10.

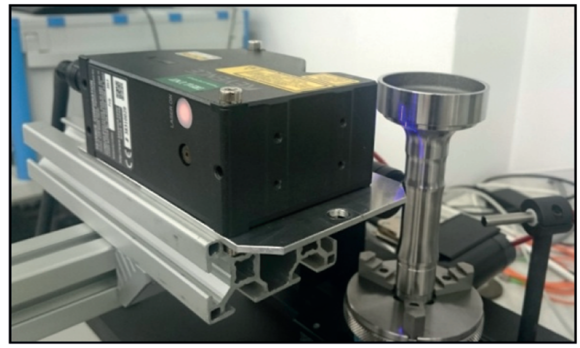


Fig. 9. Illustrative image during axial eccentricity measurement using a laser head

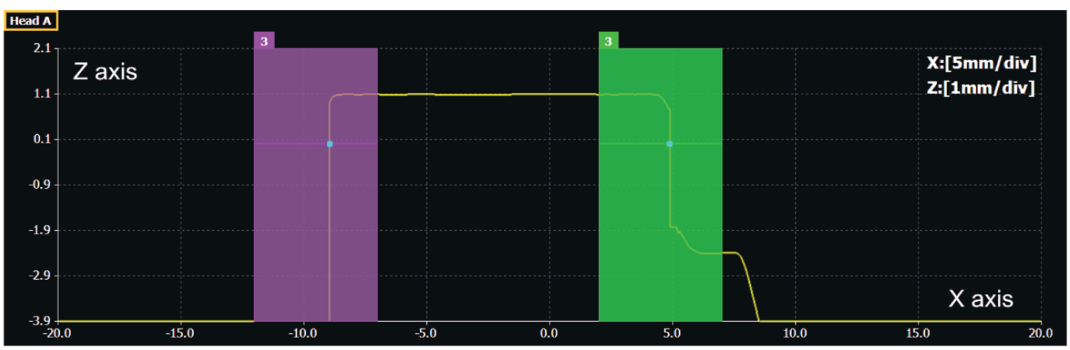


Fig. 10. An example of a registered graph Z = f (X): measured 2D profile (yellow) with measurement windows (violet and green) inside which the edge is determined

On the basis of the analysis of subsequent 2D profiles recorded during the rotation of the workpiece, the position of both edges in the X-axis is determined (independently for each of the measuring windows). Measurements are performed automatically in the laser head controller and the results in the form of a table showing the changes in the position of the edges during rotation are sent to the computer, which determines the axial eccentricity value. Measurements were also made using Laser No. 2 with a smaller measuring range, but 5 times the resolution of the X-axis (along the laser line). In this case, the position of each edge was analysed separately. Sample results of measurements using head No. 2 are shown in Figure 11.

a) b)

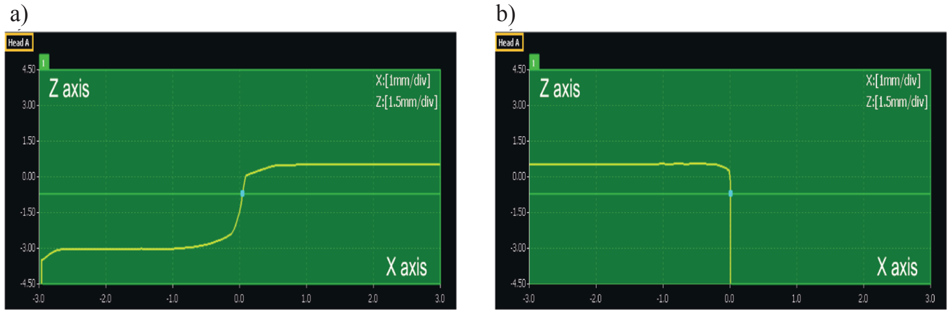


Fig. 11. Examples of a registered graph Z = f (X): a) for edge 1, b) for edge 2, measured 2D profile (yellow) with measuring windows (green)

Each edge position change was recorded in the controller memory and then transferred to the PC for further analysis. Figure 12 shows a sample graph of changes in the position of the edge during full rotation of the work piece relative to the measuring head. On this basis, calculating the absolute value of the difference between the minimum and maximum position of the edge during rotation the axial eccentricity value is determined.

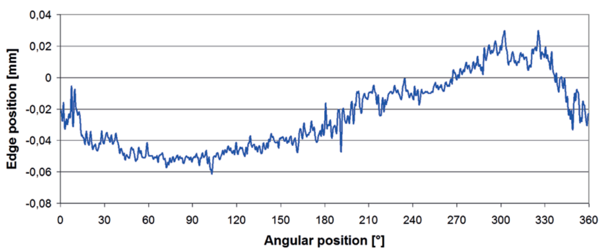


Fig. 12. An example of a registered graph of changes in the position of the edge of a workpiece as a function of an angular position

A measuring system consisting of Laser No. 2 (with a smaller measuring range and higher resolution) and a controller for on-line analysis of registered 2D profiles were selected for use in the developed solution.

2. The structure of the quality inspection module

Based on the assumed concept and technical specifications of the selected measuring devices, a 3D model of the product quality inspection module (Fig. 13) was developed.

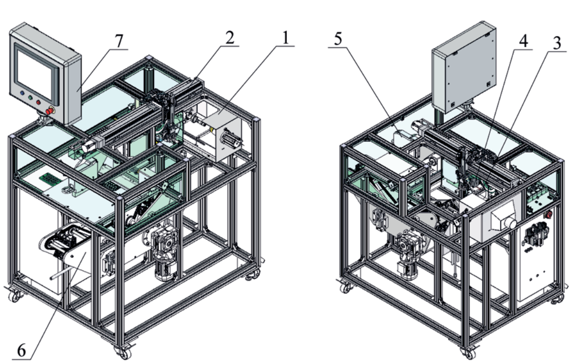


Fig. 13. A view of 3D product inspection module: 1 – cleaning module, 2 – inter-operation transport module, 3 – module for optical inspection of dome, 4 – laser depth measurement module, 5 – module for external geometry measurement, 6 – control module

An important stage in the preparation of a product that is subjected to inspection is the cleaning of the surface from the residues remaining after the production process [13]. In the assumed concept, the object to be taken for inspection from the machine by the portal manipulator is to be moved into the working area of the cleaning module of the inspection device. In the first phase, a compressed air fed from the two coaxial horizontal nozzles removes debris from the centring holes, which constitute the measurement base of the workpiece, remaining after the machining, including micro-shavings and the drops of the coolant. Further cleaning (phase II) is carried out after the workpiece has been gripped in the cone gripper and rotated. The rotating detail is blown with two nozzles: diagonal and radial. Air from a fixed slanting nozzle removes dirt from the inside of the dome. Moving along the axis of the workpiece, the radial nozzle clears the outer surface.

The cleaned items are collected by the inter-operation transport module. The module's task is to move the element between different measurement positions and, after measurements, transfer it to the preservation module.

The first of the measuring modules is the optical inspection module of the inside of the dome consisting of a device equipped with a telecentric lens and a dedicated illuminator (Fig. 14.a). The inspected detail located in the jaws of the transport module is located in the optical axis of the measurement module.

Based on the analysis of the image obtained from the camera, the inner diameter and the radial eccentricity of the dome are determined. In the next phase, the depth measurement of the dome is carried out in the module of the laser depth measurement of the dome (Fig. 14b).

Other dimensions from the dozens specified in the technological guide are controlled in the optical module for measurement of the external geometry of the workpiece. The inter-operation transport module places the detail in the cone gripper of the linear positioning module. In this module, measurements are made using two measuring devices: a 2D laser head and an optical micrometre (Fig. 15). The 2D laser head is responsible for measuring the axial eccentricity, while the optical micrometre measures the geometry and determines the radial eccentricity of the rotating surfaces.

The positioning unit consists of two precise spindles. A spindle with a cone allows the rotational of the detail necessary for measuring the radial and axial eccentricity of the inspected surfaces.

A pneumatically driven holding spindle with a precise rotary cone gripper ensures stable positioning of the workpiece during measurements. After the measurements have been completed, the inter-operation transport module transfers the details to the preservation slot. In the case of a negative inspection result, the operation of the device is suspended pending the decision of the operator (technologist). In the case of a positive

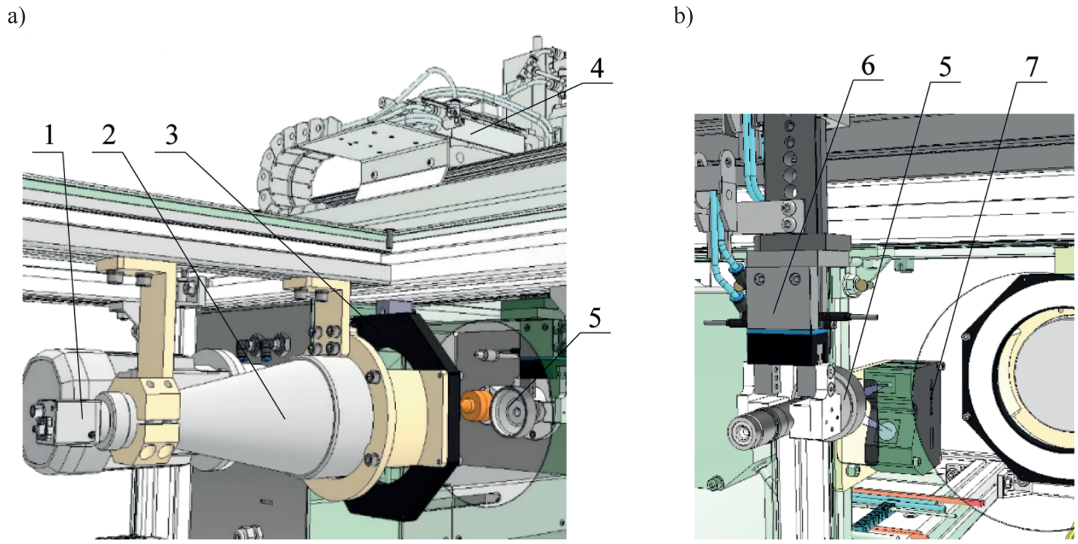


Fig. 14. **Designed measurement modules: a) optical inspection module, b) laser depth measurement module: 1 – digital camera, 2 – telecentric lens, 3 – illuminator, 4 – inter-operation transport module, 5 – 2D head**

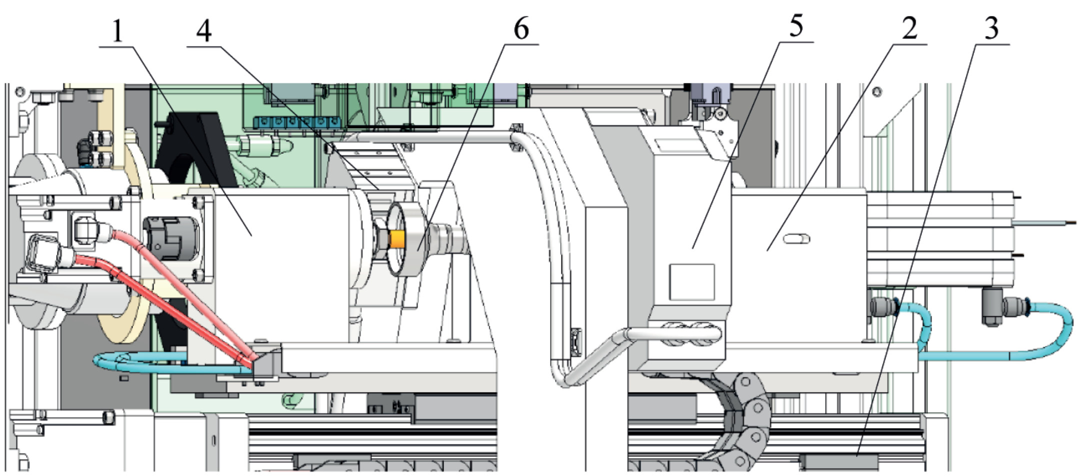


Fig. 15. **External geometry measurement module: 1 – drive spindle, 2 – holding spindle, 3 – linear servo drive module, 4 – 2D laser head, 5 – optical micrometre, 6 – inspected product**

result, the item is automatically placed in the chain carrier of the preservation module chain. Protection of the surface against corrosion is achieved by dipping the part in the preservative fluid. The details placed in the trays, which are parts of the chain conveyor, travel inside the liquid bath to the point of reception through the drip zone. The transport speed of the transporter is selected according to the duration of the measuring cycle (depending on the complexity of the workpiece).

Further work on the system will involve the production and prototype testing according to the accepted methodology [14, 15]. It will also be important to develop efficient and reliable algorithms for processing and analysing data recorded by the camera, laser heads, and optical micrometre.

Conclusions

The issues related to the automation and robotisation of manufacturing are currently the dominant trends in the development of existing manufacturing plants. Entrepreneurs strive to optimize the production process at every level – from logistic issues through the optimal use of machine working time to analyses related to the optimization of machine performance. The aim is to ensure the highest possible productivity while maintaining a high quality of product. The device, the concept of which is presented in this article, is designed as an element of a robotic system for the operation of two CNC machines.

The device described in the concept is an optomechatronic measurement module designed for automated multi-parameter quality inspection of products. Optical inspection techniques were selected for contactless measurements of several dozen parameters characterizing the product. Due to the need for full inspection of the product including most of its surface, an important issue at the design stage was to optimize the structure of the measurement system to achieve the maximum efficiency of the inspection process while ensuring the required accuracy.

It is assumed that the developed inspection system will ensure a significant increase in the economic efficiency of production by eliminating defective products according to the "zero fault" approach without interfering with the manufacturing process. The use of contactless optical and laser technologies allows high-speed measurement while maintaining high measurement accuracy. Integrating several measuring circuits in the instrument allows inspections of most product parameters and the inspection of every part produced. Quality inspection of products will be carried online, that is in parallel with the production of the next two parts. In the case of the detection of defective product, it is possible to stop the production, correct the parameters of the CNC machine, and return to production.

The implementation of the developed quality inspection system will allow direct monitoring of the quality of manufactured parts, and indirectly the technical condition of the entire production setup, by tracking product quality statistics, including changes in selected parameters, indicating degradation of the machine or cutting tool. The developed device, along with the manipulator, will allow the optimization of the utilization of the working time of CNC machines and machining parameters, contributing to the economic efficiency of the production setup.

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