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THE OPTOMECHATRONIC SYSTEM FOR AUTOMATIC QUALITY INSPECTION OF MACHINED WORKPIECES

Key words: production, quality inspection, non-contact measurement, optomechatronic technologies.

Abstract: Systems for the automated multi-parametric quality inspection of products manufactured with CNC machines are a key factor in increasing production efficiency. The optomechatronic measuring system developed by the authors of the article enables automatic non-contact quality inspection of products manufactured with CNC machines with efficiency corresponding to the manufacturing process in accordance with the "zero fault" principle. The integrated quality inspection system uses specialised optoelectronic modules to measure dimensions and shape. The developed inspection system was implemented in the machining industry. The solution is dedicated to production systems in accordance with the Industry 4.0 concept.

System optomechatroniczny do automatycznej kontroli jakości wytwarzanych wyrobów

Słowa kluczowe: produkcja, kontrola jakości, pomiary bezstykowe, technologie optomechatroniczne.

Streszczenie: Systemy automatycznej wieloparametrycznej kontroli jakości wyrobów wytwarzanych na maszynach CNC stanowią kluczowy czynnik w podwyższaniu efektywności produkcji. Opracowany i przedstawiony przez autorów optomechatroniczny system pomiarowy umożliwia automatyczną bezstykową kontrolę jakości wyrobów wytwarzanych na maszynach CNC z wydajnością odpowiadającą procesowi wytwarzania zgodnie z zasadą „zero braków". W zintegrowanym systemie kontroli jakości zastosowano specjalizowane moduły optoelektroniczne umożliwiające pomiary wymiarów i kształtu. Opracowany system inspekcji został wdrożony w przemyśle maszynowym. Rozwiązanie jest dedykowane do systemów produkcyjnych zgodnie z koncepcją Industry 4.0.

Introduction

Continuous increase in production efficiency through automation and the increase in the efficiency of manufacturing processes while ensuring the high quality of products is the primary goal of enterprises striving to strengthen their position on the market. The consequence of actions taken in this area is the integration of production systems, the key element of which is the digitization and intelligent use of data collected during the manufacture of the product to improve the quality and efficiency of the production process. The directions for the development of factories of the future are outlined by the Industry 4.0 concept, which includes the use of innovative solutions enabling the integration of manufacturing processes and quality inspection in modular structures of production lines [1], [2]. Thanks to the use of robotics and automation, it is possible to significantly increase production efficiency. However, often a critical limitation of high-throughput production processes is quality inspection, which, in the case of complex products, requires considerable time and the use of different measuring techniques. An example of this is the production of rotational-symmetric metal products by machining methods, where many parameters characterizing dimensions, geometric shapes, and surface quality are inspected. The quality inspection of such a product often requires the use of several specialized measuring devices, including CMM coordinate measuring machines. In many companies, until now, the product inspection is performed manually, often by a machine operator using callipers, micrometres, and dial indicators. In the case of production of long series, the inspection is performed for randomly selected copies of products. A significant breakthrough in the quality inspection automation was due to the development of optomechatronic technologies enabling non-contact measurements of geometric dimensions as well as surface inspection. The development of non-contact optical measurement methods is currently dominant in relation to the following methods: mechanical, electrical, pneumatic, and ultrasonic [3]. One of the directions of the development of advanced metrological devices is hybrid measuring stations using non-contact optical measurement methods and contact methods [4]. The hybrid system MarShaft SCOPE 600 plus 3D is dedicated to the factories of the future of Industry 4.0 [5]. The device is adapted to cooperate with a robot that supplies products for inspection. Network communication allows the transmission of data on exceeding the permissible tolerance values to the CNC machine.

Currently, advanced optoelectronic devices for measuring geometric values are available on the market, including 2D/3D laser profilometers, confocal profilometers, and optical micrometres that can be used in integrated multitask measurement systems. Workshop laser scanner 2.5D Sylvac Optical Vertical Measuring Scan F60L allows measurements of diameters and lengths of shafts with a repeatability of approx. 2 μm [6]. At the same time, research and development works are carried out in the area of inspection methods dedicated to industrial applications. In order to shorten the time spent on quality inspection, systems are proposed to measure the manufactured product directly on the CNC machine. Examples of such solutions include the shaft circularity inspection system on the machine using the vision method [7] and the surface roughness inspection system [8]. The system of surface roughness prediction and dimensional deviations using mathematical models (including Response Surface Methodology – RSM) is presented in [9]. The experimental integrated system for measuring the diameter and the circularity of the product with an accuracy of 0.5 μm when fastened on a CNC machine is presented in [10]. In-line measurement of the 3D shape of the workpiece on the machine enables an interferometric laser-Doppler distance sensor (LDD sensor) [11]. In the experimental system, the scatter of the measurement results was approx. 2 μm. The limitation of in-line inspection methods is the sensitivity to impurities occurring on the surface of the object during processing. An important issue in the design of the vision system for the inspection of objects with slender shapes is the optimization of the field of observation. In addition to dedicated line cameras in this case, it is also possible to use multi-camera systems that enable inspection based on the analysis of images of particular parts of the object [12]. In the case of products with complex shapes, e.g., screws, various measuring methods are used, as well as image processing algorithms to determine the thread parameters. Most of the parameters describing the thread can be measured using contactless vision methods [13].

The basics of the methodology of designing specialized multi-camera vision systems of rotational symmetric objects, as well as sample solutions of the structures of imaging systems using dedicated illuminators and lenses are presented in [14]. When designing optical measuring systems intended for use in industrial conditions, many factors that may influence the accuracy of measurements should be taken into account [15]. One example is measurements of geometric dimensions that require precise determination of the contours of the item being inspected. Interferences in the image are the result of phenomena of light interaction with the edge of the object, which results in light reflection in different directions, depending on the surface microstructure and scattering. In order to determine the geometrical dimensions, dedicated edge detection algorithms are used, using, among others, Prewitt, Canny, Sobel, Roberts, Laplacian of Gaussian, and Zero-crossings algorithms [16]. The quality of the images obtained and the measurement error depend to a large extent on the lighting conditions. Measurements of the geometrical dimensions of the workpiece with the use of a tool as a measuring tip are presented in [17]. The results of the experiments showed that it is possible to measure with an accuracy of approx. ±2 μm. At the same time, however, the authors pointed out that the correctness of the measurements depends significantly on the quality of the electrical contact between the tool and the workpiece.

The currently used methods and devices for quality inspection of rotational-symmetric products manufactured with CNC machine tools are very time-consuming and allow only selected parameters to be measured. Some of the offered contactless and contact measuring systems are not dedicated to work in workshop conditions in the production area. The lack of integrated systems for automatic multi-parameter quality inspection of products in accordance with the "zero fault" principle is still a technical barrier in increasing the efficiency of the production process. In the perspective of the development of advanced measurement systems tailored to the requirements of factories of the future, an indispensable element is network communication with a machine that allows automatic on-line adjustment of machining process parameters based on data on deviations from the quality inspection of manufactured products.

1. System structure

The developed prototype optomechatronic system is intended for the inspection of the metal products machined with CNC machines (Fig. 1). The integrated production system consists of a semi-product buffer, two CNC lathes, and an optomechatronic inspection system which includes the following: cleaning module, inspection module, selection module, an outfeed module, and a manipulator to perform all the movements of the machined parts between the elements of the nest [18].

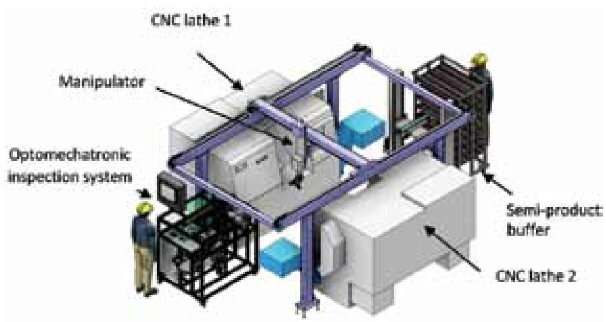


Fig. 1. General view of the integrated system of production and quality inspection of products

The internal manipulator of the inspection system is a rectangular system with three degrees of freedom. The X-axis is driven by the ball-screw mechanism and a servo motor, while the latter two are pneumatically actuated, as they work in an end-to-end mode, positioned by hard limits and their speed is controlled by damper valves. There is an additional linear positioning module with ball-screw and a servo motor built in the micrometre module, which is part of the inspection module. Since the inspected part is handled between the nest manipulator, cleaning system, local manipulator, optical micrometre system, and selection systems, there exists a collision point in the system. To ensure proper timing of the operation of the system, uninterrupted interaction to the production nest, smooth work of moving parts as well as their safety, it was necessary to program proper control procedures within the control system of the device. With the standard approach to industrial system, the safety is often ensured with the use of software delays between the subsequent operations; however, in the case of this system, any delays were undesirable and therefore the safety of the movement was ensured by use of physical sensors placed on as many positions as possible, redundant checking the states of the linear positioning modules, and hardcoded movement limits.

The communication between the inspection system and the production nest is performed at two levels of complexity. The basic level is a set of binary lines for simple communication with the manipulator, which directly interacts with the inspection system by putting the element into the cleaning module. The higher level is based on an Ethernet communication, which allows the exchange of sophisticated data, such as images, part feature tables, and inspection system states.

The safety circuit allows the mutual dependency of the inspection system and the production nest. Emergency stop on any component of the production nest causes the emergency state in other components. Since the inspection system could be offered as an optional component, the component dependency is also configurable. Moreover, it is possible to select which functions of the safety circuit are dependent, that is, it is possible to allow the inspection system to be reset from the production nest or to not allow. In the latter case, the separate actions of operator are required on the CNC machines and on the inspection system.

2. Measurement methods

The developed optomechatronic system is a hybrid system consisting of specialized measurement methods enabling the inspection of metal products with axial-symmetric shapes in the range of programmed parameters. The product range includes shafts with diameters up to 60 mm and lengths up to 160 mm and weights up to approx. 0.8 kg (Fig. 2). Possible measurement parameters include diameters, lengths, and radial and axial run-out.

a)

b)

Fig. 2. The scope of measurement possibilities of the developed method in relation to the prototype of the optomechatronic inspection system (a); sample element produced in an integrated production and quality inspection system subjected to inspection (b)

The high level of system versatility is due to the use of optoelectronic modules enabling measurements of multi-diameter shafts. Quality inspection covers geometric dimensions with regard to shape and position errors. According to the "zero fault" principle, 100% of manufactured parts are subjected to inspection.

Product inspection is carried out using contactless measurement methods in the following steps (Fig. 2):

– Measurements related to the inspection of the face of the shaft (carried out after gripping the detail in the jaws of the manipulator), and
– Measurements related to the inspection of the side surface, requiring the product to be displaced or turned (realized after fastening the part in the claw grippers).

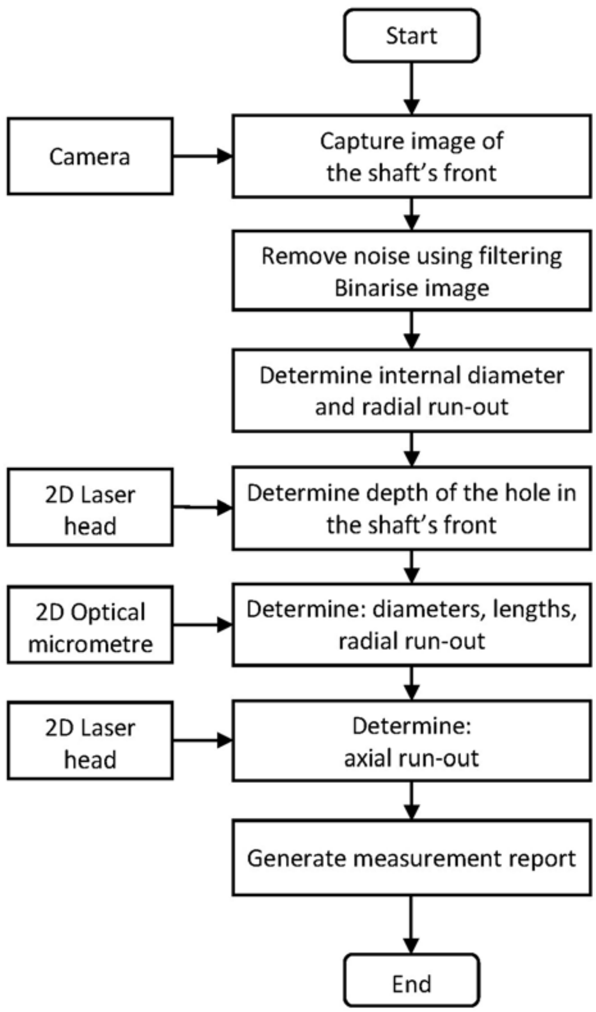


Fig. 3. Flowchart of measurement algorithm

The product inspection process is preceded by automatic cleaning of its surface with the use of a pneumatic nozzle.

Inspection of the face of the shaft includes measurements of the inside diameter of the hole, measurements of radial run-out, and measurements of the depth of the hole. The measurements are made using two measuring methods (Fig. 4):

– Vision method (digital camera with telecentric lens), and
– Laser triangulation (2D type measuring head).

a)

b)

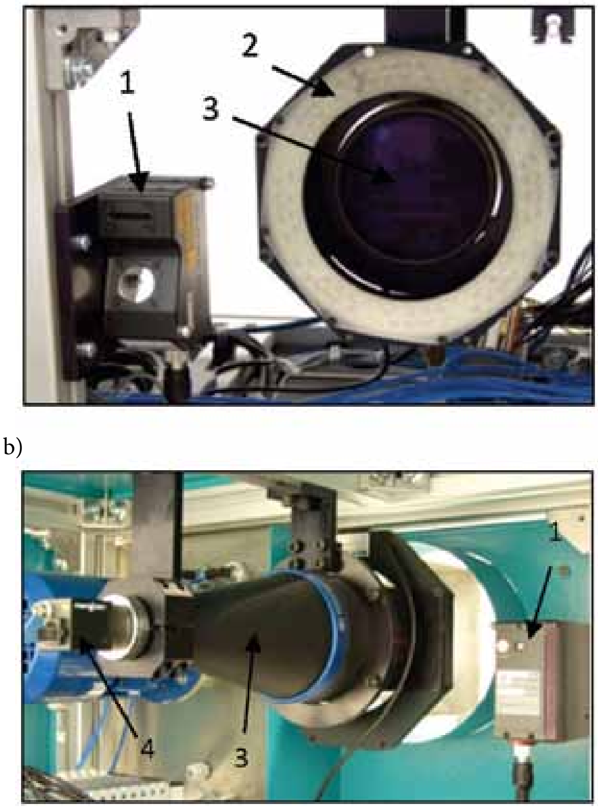


Fig. 4. Shaft front inspection module: a) front view, b) rear view; 1 – 2D laser head, 2 – LED ring illuminator, 3 – telecentric lens, 4 – digital camera

The inspection is carried out sequentially, when moving the part in the jaws of the manipulator. First, the internal diameter measurement and radial run-out measurement are performed using a vision module equipped with a digital camera [20] and a telecentric lens [21]. The telecentric lens provides approximately constant image magnification over the entire working range of the observation. The basic parameters of the vision system are shown in Table 1. The experimentally determined resolution of the vision system is 28 μm.

Table 1. Basic parameters of the used vision system

Digital camera

Parameter	Value
Sensor type	CCD mono
Sensor size	2/3"
Resolution	2448x2048 px

Telecentric lens

Parameter	Value
Field of view	Ø 70.9 mm
Working distance	181.8 mm
Depth of field	67 mm

Based on the developed image analysis algorithms (Fig. 5), the geometric centre of the face is first determined, followed by the determination of the inner diameter and the radial run-out.

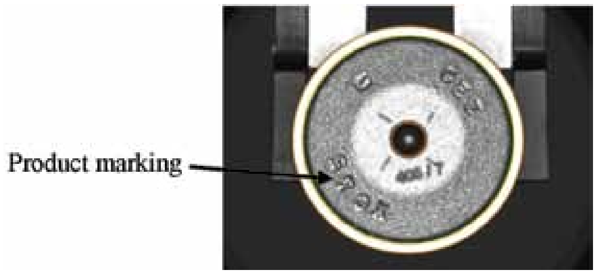


Fig. 5. Sample image of the face of the shaft registered by the camera

In the second stage, the hole depth measurement is performed using a 2D laser head [22]. The basic parameters of the measuring head used are shown in Table 2.

Table 2. Basic parameters of the measuring laser 2D head [21]

Measurement parameter		Value
Range	X axis	25 ÷ 39 mm
	Z axis	± 23 mm
Resolution	X axis	50 µm
Repeatability	X axis	10 µm
	Z axis	0.5 µm
Non-linearity	Z axis	± 0.1 % of range

The results of the scanning process are the coordinates of points belonging to the laser line projected on the surface of the object, forming a 2D surface profile. On the basis of the analysis of the registered profile of height changes, the depth of the hole is determined as the difference in levels in specific areas (Fig. 6).

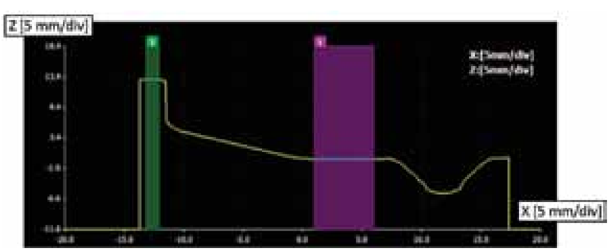
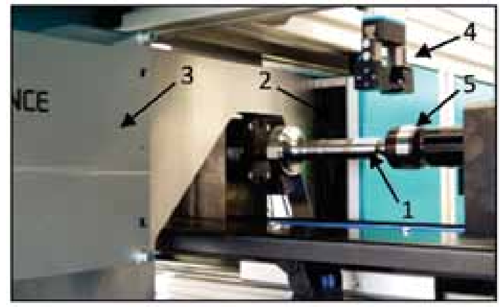


Fig. 6. An example of a measured 2D profile (yellow colour) with marked measurement windows (green and purple), on the basis of which the depth of the hole in the face of the shaft is determined

After the measurements are made on the face of the shaft, the manipulator moves the part to the next measuring module where the product is clamped in the claw grippers. The inspection of the side surface of the products includes measurements of diameters, distances, depths, and radial and axial run-out values. Measurements of the side surface are made using two measuring devices: an optical micrometre and a 2D laser measuring head (Fig. 7).

a)



b)

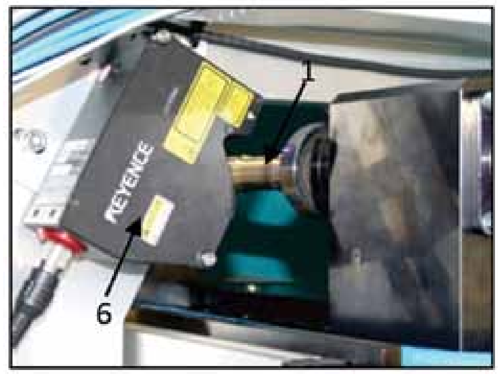


Fig. 7. Measuring module for inspecting the side surface of the shaft: a) front view, b) rear view; 1 – shaft, 2 –- transmission head of the optical micrometre, 3 – receiving head of the optical micrometre, 4 – gripper, 5 – claw gripper, 6 – 2D laser head

The optical micrometre consists of a head generating a parallel light curtain (transmitter) and a receiving head with a photosensitive matrix (Table 3). The tested product, placed between the transmitting and receiving head, interrupts the projected light curtain. On the basis of the created shadow, the receiving head measures the contours of the detail, whose position allows the determination of the outer diameter of the rotational-symmetric product.

Table 3. Basic parameters of the optical micrometre used [21]

Parameter	Value
Measurement range	0.8 ÷ 120 mm
Distance between heads	400 ± 100 mm
Measurement repeatability	± 0.3 µm
Measurement accuracy	± 8.0 µm (in the range below 40 mm) ± 16.0 µm (in the range above 40 mm)
Sampling frequency	≤ 16 kHz

In order to precisely scan the side surface of the detail, a linear drive was used with position control by means of a linear encoder [23]. The basic parameters of the encoder used are presented in Table 4. The signals from the incremental encoder enable direct triggering of the optical micrometre measurement with a fixed step.

Table 4. Basic parameters of the measuring encoder used [22]

Parameter	Value
Resolution	1 µm
Measurement range	270 mm
Accuracy	± 5 µm
Max. linear velocity	25 m/min

A sample diagram showing the measured product diameters is shown in Fig. 8. At the stage of processing and analysis of the measurement results, the areas regarding the claw grippers are rejected.

Radial run-out measurements are carried out using an optical micrometre. During the measurements of radial run-out, the product is put into rotation. On the basis of changes in the position of the product edge during rotation, the radial run-out value is determined. A sample graph of vertical edge location changes is presented in Fig. 9.

A 2D laser head from Keyence [22] was used to measure axial run-out, the parameters of which are presented in Table 5.

Table 5. Basic parameters of the used 2D laser head

Measurement parameter		Value
Range	X axis	6.5 ÷ 7.5 mm
	Z axis	± 2.6 mm
Resolution	X axis	10 µm
Repeatability	X axis	2.5 µm
	Z axis	0.2 µm
Non-linearity	Z axis	± 0.1 % of range

During the measurement of axial run-out, the product is put into a rotational movement. Based on the scanned 2D profiles, the edge position value is determined along the axis of rotation of the product (Fig. 10). During rotation, further values of the edge

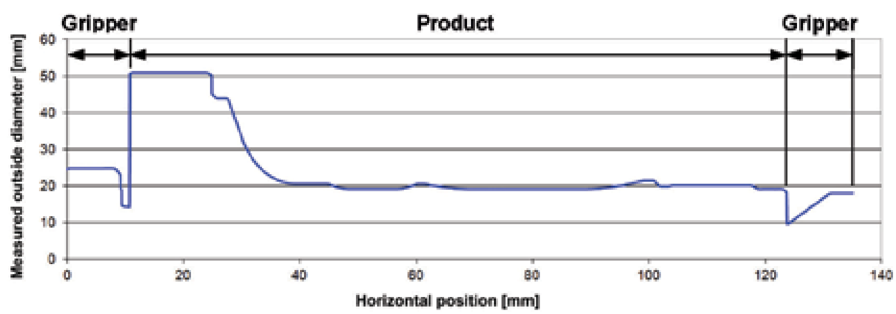


Fig. 8. An example of a scanned profile of product diameters

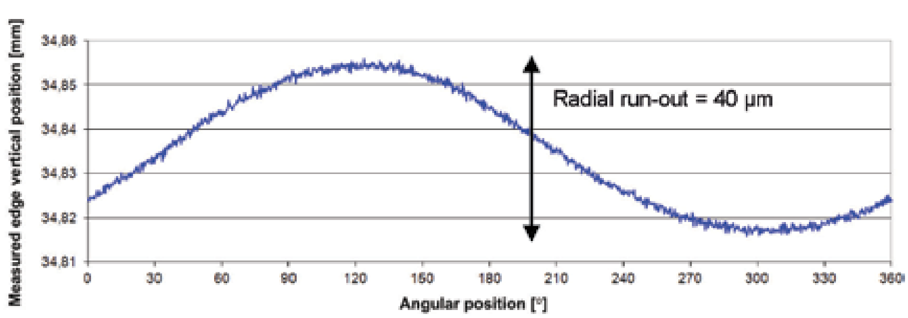


Fig. 9. An example graph of the vertical position of the product edge during rotation

a) b)

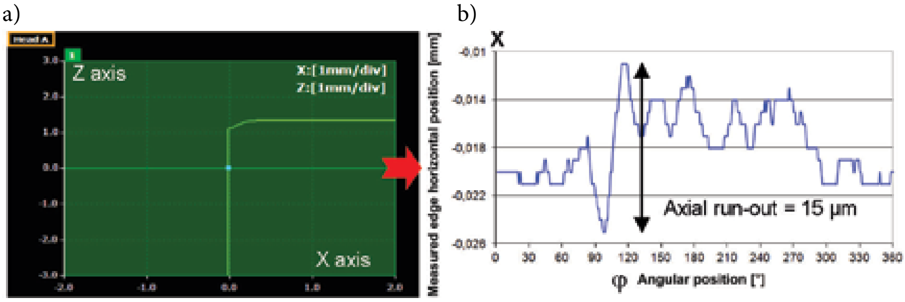


Fig. 10. Examples of results obtained during the measurement of axial run-out: a) measured profile with a set measuring tool for determining the position of the edge along the axis of shaft rotation, b) chart of changes in the horizontal position of the edge (X) during the rotation of the product (φ)

position are collected, on the basis of which the axial run-out value is determined. An exemplary diagram of changes in the horizontal edge position is shown in Fig. 10b.

3. Experimental results

The developed prototype has been tested in order to verify the obtained technical and functional parameters. The tests consisted of carrying out a series of measurements for a selected product manufactured in an integrated production and quality inspection system (Fig. 2b). Each element representing the selected product has been measured ten times using the developed system. The products were placed in claw grippers in a random angular orientation. The values of the maximum spread and the difference between values measured by the system and reference measurements are presented in Table 6.

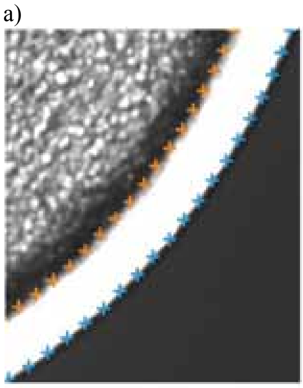
In the case of several parameters, the reference data were not available in the measuring cards provided by the manufacturer. The difference to reference measurement was determined in relation to the average of the measurements made using the developed system. In the case of shaft optical inspection module, the difference in the results obtained is due to the resolution of the imaging system, which is 0.028 mm. In addition, due to the geometry of the detail and the type of internal surface treatment (Fig. 11), the course of the determined edge relative to the centre of the detail has local extremes that influence the determined parameter values. Therefore, it is necessary to perform smoothing operations (smoothing profiles) to determine the run-out parameter.

To determine the internal and external diameters, the Pratt matching algorithm was used, which minimizes the average distance between the result and the given points [25]. The difference in the results obtained is due to the resolution of the imaging system, which is 0.028 mm. Another geometric parameter that was analysed was the depth of the hole in the shaft's face. Based on the analysis of the recorded height profile, the difference in levels in specific areas is determined, which is the measurement result. The spread of results, which is much larger than the measurement resolution of the laser head used, is caused by the marked product markings, visible in the camera image (Fig. 5), which may be

Table 6. Measurement results

Parameter	Spread $_{max}$ [mm]	Difference $_{max}$ [mm]
Module for optical inspection of shaft face		
Inner hole diameter	0.054	No reference
Radial run-out	0.104	No reference
Module for laser measurement of depth of hole in the shaft face		
Depth	0.102	No reference
Module for measurement of side surfaces of shaft geometry		
Radial run-out, pos. 1	0.012	0.029
Radial run-out, pos. 2	0.017	0.017
Diameter pos. 1	0.081	0.030
Diameter pos. 2	0.005	0.009
Diameter pos. 3	0.005	0.016
Diameter pos. 4	0.009	0.006
Diameter pos. 5	0.005	0.013
Diameter pos. 6	0.004	0.011
Diameter pos. 7	0.005	0.014
Diameter pos. 8	0.007	0.013
Diameter pos. 9	0.018	0.087
Diameter pos. 10	0.009	0.031
Module for laser measurement of radial run-out		
Radial run-out, pos. 1	0.034	No reference
Radial run-out, pos. 2	0.014	No reference

a)



b)

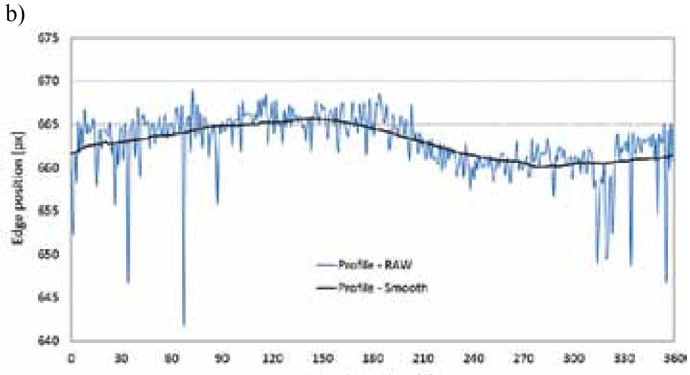


Fig. 11. Inspection of the face of the shaft: a) sample image region b) profile of the distance of the inner edge in relation to the centre of the detail before (black colour) and after the averaging operation (blue colour)

randomly located in the analysis area and interfere with the measurement. In the developed system, most of the parameters are measured using an optical micrometre during a linear movement. When the product is rotated in certain positions, radial run-out is also determined. Measurements of diameters are carried out in the positions specified in the product documentation. The visualization of the outside diameter measurement of the aperture in the face of the shaft is shown in Fig. 12.

For the horizontal measurement position relative to the left edge of the product x = 6.99 mm, the diameter value is 51.019 mm, while for the position x = 7.08 mm, the measured diameter size is 51.021 mm. The difference may result from the optical resolution of the micrometre, the geometry of the object, or the accuracy of positioning the product in the gripper. Therefore, the average value determined on the section with a length of 0.2 mm is assumed as the result of the measurement.

The developed system was implemented in industrial conditions (Fig. 13).

The results of the tests confirmed the possibility of performing product inspections in about 30 seconds per piece, corresponding to the speed of product machining in the system of two CNC machines.

Conclusion

The review of the state of the art shows that the lack of automatic multi-parameter quality inspection systems of products integrated with production with CNC machines is a significant barrier to increasing production efficiency. Specialized measuring instruments commonly used allow the measurement of selected parameters. The necessity to carry out quality inspection of the product on several positions extends the production process time significantly.

The authors of the article proposed a solution that allows overcoming this barrier. The integrated optomechatronic measuring system developed implements automatic multi-parameter quality inspection of products manufactured with CNC machines. During one cycle, dozens of programmed parameters are measured. The integrated system structure includes optoelectronic modules that provide non-contact measurements of geometric dimensions. Information on existing deviations of parameters is presented on the operator's panel and can be used directly to correct the machining parameters on CNC machines. Movement and positioning of the product in subsequent inspection positions is carried out by the mechatronic module. The developed system is

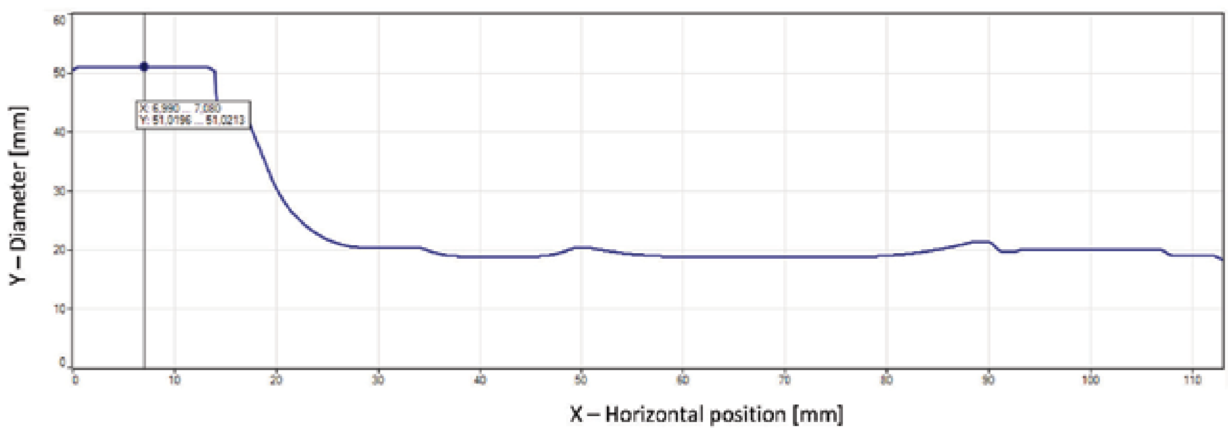


Fig. 12. Sample shaft profile (Source: Authors)

a) b) c)

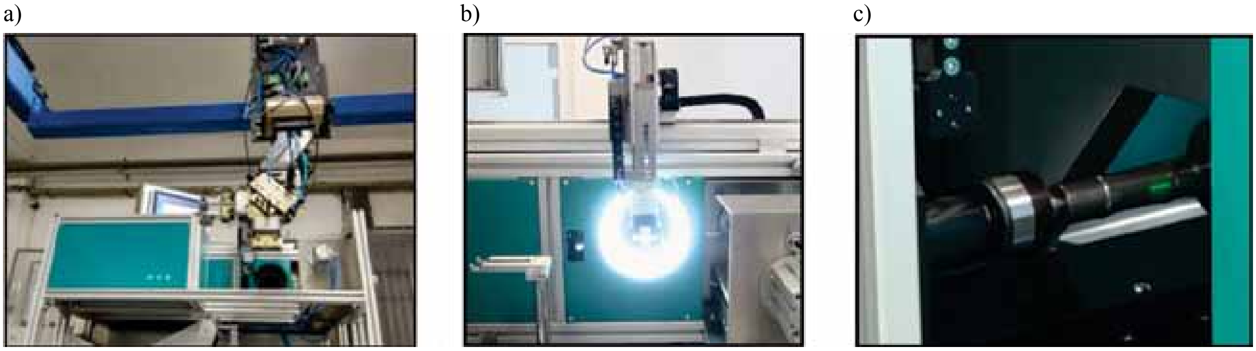


Fig. 13. Prototype optomechatronic automatic product inspection system [18]: a) general view at the workplace, b) inspection of the shaft face, c) measurements of the side surface of the shaft

a highly universal solution, adapted to inspect a range of products varied in terms of shapes and dimensions. The limitation is the need to develop dedicated algorithms for image processing and analysis for a new range of products and their experimental verification. Ensuring the high accuracy of measurements requires the use of specialized measurement modules, appropriate lighting methods, and the development of measurement data processing algorithms. During the research work, it was found that light scattering at the edges of metal products that could disturb the measurement result is a significant problem. Additional challenges occur with the positioning of the inspected product with grippers, and the solution is using calibration shafts and additional statistical analyses.

The conducted tests of the developed system confirmed the achievement of the planned technical and functional level. The developed inspection system was implemented in a company producing metal products for the machine industry. The solution is dedicated to production systems in accordance with the Industry 4.0 concept.

Continued research and development work focuses, inter alia, on improving algorithms for determining dimensional parameters and developing a module for automatic correction of machining parameters on a CNC machine in a feedback system.

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