Application of the SMART Optical Displacement Sensors in Measuring the Diameter Deviation of C45 Steel After the Turning Process

Martin Miškiv-Pavlík, Jozef Jurko, Alexander Hošovský, Vratislav Hladký, Kamil Židek, Igor Petruška, and Tadeusz Eugeniusz Zaborowski

1 Introduction

As industrial production is increasingly changing from manual labor to highly automated and demanding work, the application of modern measurement technology is a main part of this production. One of the most important tasks in the technical production industry is the inspection of products. Devices with contact measurement methods of the obtained parameters are still used for quality control of machined surfaces. In these contact measuring methods, the measuring contact is in direct contact with the machined surface. This direct contact of the measuring contact with the machined surface is one of the negative effects of the measurement. On the one hand, the contact surface of the measuring device is damaged, and on the other hand, the surface to be measured is damaged. One of the many possible uses of contactless sensors is to measure deviation of surface from workpiece diameter after process of turning. This method allows rapid detection of defects on the workpiece surface without sending the product to quality control after production [1–8].

The chapter main thesis was the application of optical contactless sensors in the measurement of the deviation parameter from the workpiece diameter of C45

M. Miškiv-Pavlík · J. Jurko (✉) · A. Hošovský · V. Hladký · K. Židek
Technical University of Košice, Faculty of Manufacturing Technologies, Prešov, Slovakia
e-mail: martin.miskiv-pavlik@tuke.sk; jozef.jurko@tuke.sk; alexander.hosovsky@tuke.sk; vratislav.hladky@tuke.sk; kamil.zidek@tuke.sk

I. Petruška
University of Prešov in Prešov, UNIPO, Prešov, Slovakia
e-mail: igor.petruska@unipo.sk

T. E. Zaborowski
Instytut Badań i Ekspertyz Naukowych, Gorzów Wielkopolski, Poland
e-mail: tazab@sukurs2.pl

L. Knapčíková, D. Peraković (eds.), *7th EAI International Conference on Management of Manufacturing Systems*, EAI/Springer Innovations in Communication and Computing, https://doi.org/10.1007/978-3-031-22719-6_6

steel after the turning process. As a comparison to optical sensors, a mechanical micrometer was used in the experiment as a standard for the measured values. In this experiment, we demonstrated the feasibility of using these sensors to directly detect surface damage and other undesirable features of processed materials in processing centers, eliminating the need for post-processing quality control increase.

2 Optical Sensors Measuring Literature Review

In contrast to contactless testing, many traditional distance measuring devices such as micrometers and calipers make contact with the workpiece surface. This method involves contact that damages not only the instrument but also the object being measured [9].

If the object to be measured is not fixed or intended to move, the measurement results will be inherently unstable and inconsistent on subsequent measurements. The current market for sensors is growing dynamically. With over 1000 different sensor types in different countries, choosing the right sensor type for a particular application can be difficult. Machining technology is realized in the system machine, tool, and workpiece. In relation to the machine, Kishore et al. applied optical sensors vibration detection sensors to monitor the life of a diesel engine, based on the amount of measured vibrations (distance deviations) it produced [10, 11, 12] (Fig. 1).

Sensors are defined as units capable of detecting errors to defined principles. The head of sensor as the key part of the device is the interface between the external stimulus and the internal components for processing and further analysis

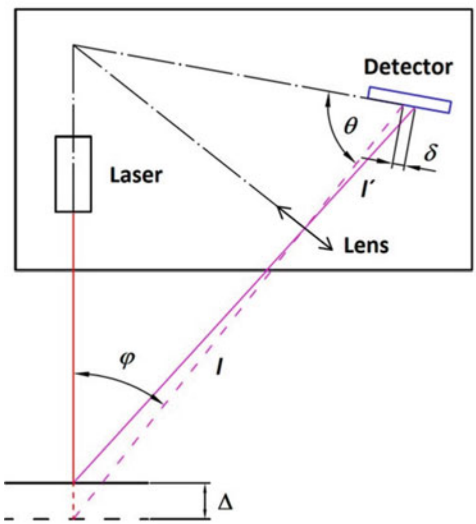


Fig. 1 Laser displacement triangulation sensor scheme [12]

of the information measured during the application [13, 14]. The main principle of this measuring method is application of polychromatic white light. This light is projected from the sensor head through a multi-lens onto the workpiece surface. The so-called confocal lens arrangement is used, in which the light is divided into colored components with different wavelengths by the natural diffraction of light. The reflected radiation to the confocal aperture of the sensor, through which only focused radiation of a specific wavelength reaches the sensor. The light quantity returned to the optical receiver changes depending on the position and distance of the workpiece. In a study, Zou et al. describe the application of non-contact sensors using a neural network in the detection of points on the surface of the workpiece, on the basis of which they have developed an active control of machining during the process. Based on the elimination of spindle deflection and accurate measurement of the center axis of the workpiece, they were able to create a 3D model of the measured workpiece and compare it with the resulting workpiece after the process of turning. In this way, they were able to detect the error in serial processing. Yu et al. used a chromatic confocal sensor in their study to measure the unevenness (thickness) of transparent materials. This study showed that with proper illumination, it is possible to use confocal sensors to measure not only metallic materials, but also materials such as glass and liquids with a measurement error rate of only 2% [15–19].

This type of sensor can be used to optimize, control and diagnose production reliability based on workpiece features on the surface. Laser scanners are ideal for these applications due to their high speed, repeatability, and accuracy of up to 1 micron. Fu et al. designed a measurement scheme using two confocal sensors facing each other, with the help of which he measured the topographic changes of the surface of the machined material directly after the machining process. The measurement system was implemented in a robotic arm, and the distance and angle measurements were adjusted during the measurement based on the computer-aided design model of the respective component. Experimental data confirm the ability of this system to measure surface roughness in the range Ra 0.002–0.007 mm ($\lambda c/\lambda s$ 300, accuracy was 5%). Cheng et al. used a monochromatic confocal sensor in the measuring process of the workpiece surface with the method of a straight line along the surface, creating a topographic map of the machined product. Measured data proved that the proposed system can achieve accuracy comparable to mechanical laboratory conditions. The measurement error is 0.001 mm. Since the current measuring mechanisms are mainly used in development processes, the present chapter can be used for new applications [20–23] (Fig. 2).

3 Research Methodology

As mentioned in the previous chapter, two types of optical deviation sensors were used in the experiment, both of which operate on the same principle, namely the insensitivity of the light reflected from the workpiece back to the sensor. Although

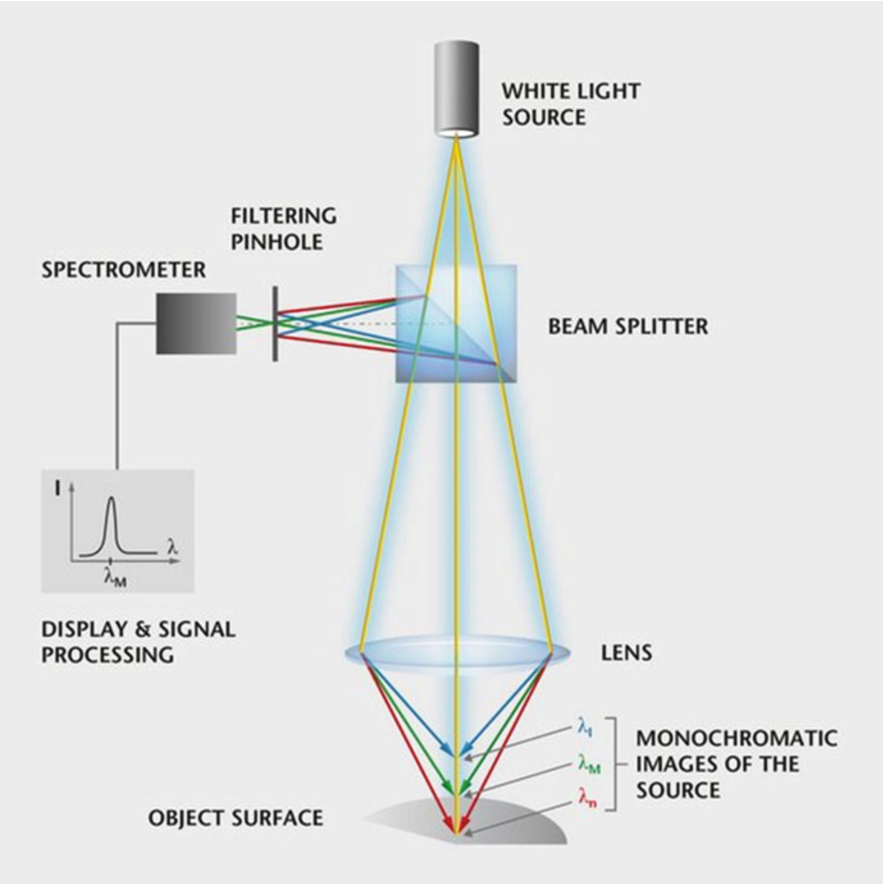
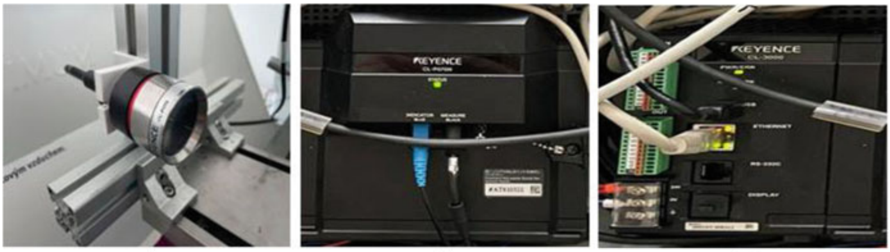


Fig. 2 Principle of confocal measuring sensor [23]

the principle of these technologies is almost the same, the circuit diagram for these sensors is not.

3.1 Confocal Sensor

In the case of confocal (CS) sensor, there is no need to application of additional hardware components. The data are written directly into the software database, which is the biggest advantage in comparison to other measuring devices that require the manual input of measured data. With the increasing distance from the sensor to the measuring workpiece, the inaccuracy of the measurement also increases, what presents the biggest issue of these types of sensors. Besides the limitation of distance



A B C

Fig. 3 Measuring scheme of confocal sensor (CS)

A B C D

Fig. 4 Measuring scheme of triangulation sensor (LTS)

in the measuring process, other disadvantages are see-through materials or glossy types of surfaces, which affect the measurement accuracy.

From Fig. 3 the wiring scheme of the measurement system can be briefly seen. Applied measuring system consists of the measurement head of the Keyence CL – P070 (A) with sensor installed on the rotary holder of the (Leadwell-T5) cutting tool, to achieve a dynamic type of measurement for the machined workpiece. All digitized values of the sensor head were transmitted by means of an amplifier Keyence CL – 3000 (C) to the communication module Keyence CL – P070N (B), where microscopic irregularities of the workpiece diameter could be observed via Ethernet to the software (Navigator).

3.2 Laser Triangulation Sensor

In the experiment part, we prepared a measurement system, which scheme is shown in Fig. 4.

The measurement system consists of measuring head (A) Keyence IL100. Its measuring range is 70–130 mm, measuring spot diameter (400 × 1350) µm which depend on the workpiece distance, repeatability 4 µm, linearity ±20 mm, and weight 75 g.

The communication unit (B), DL – PN 1. These elements are connected to the sensor head via an extension cable and are connected to the PLC (C), Siemens 1511C via the profinet module. The switch unit (D), Siemens XB005 is used as a boundary (connection) via ethernet between the PLC and the evaluated unit (PC–TIA Portal software).

4 Experimental Measuring

The first objective of this chapter was to test the possibility of using optical displacement sensors to measure the deviation of the diameter of round C45 steel machined under the same turning conditions but with another measuring devices (CS, LTS) (Fig. 5).

The basic parameters of the experimental workpiece before machining were diameter $d = 14.99$ mm and length $l = 88.8$ mm.

The machining conditions in the turning process were feed (0,28 mm), cutting speed (60 m/min), and cutting depth (0,1 mm) (Fig. 6).

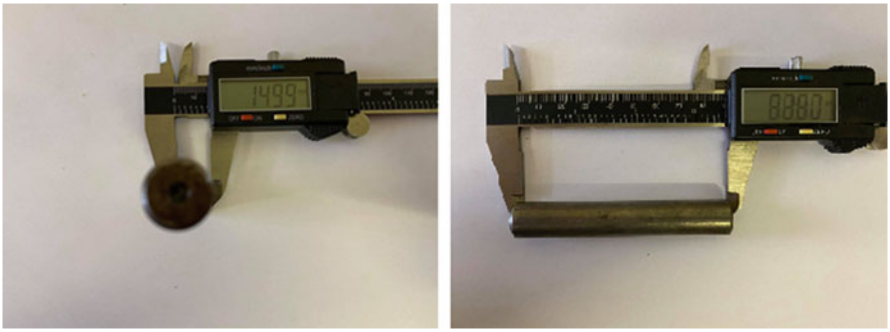


Fig. 5 Diameter measuring of the C45 sample

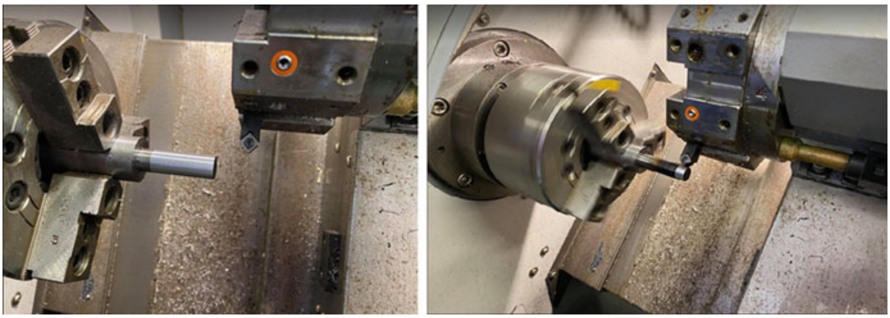
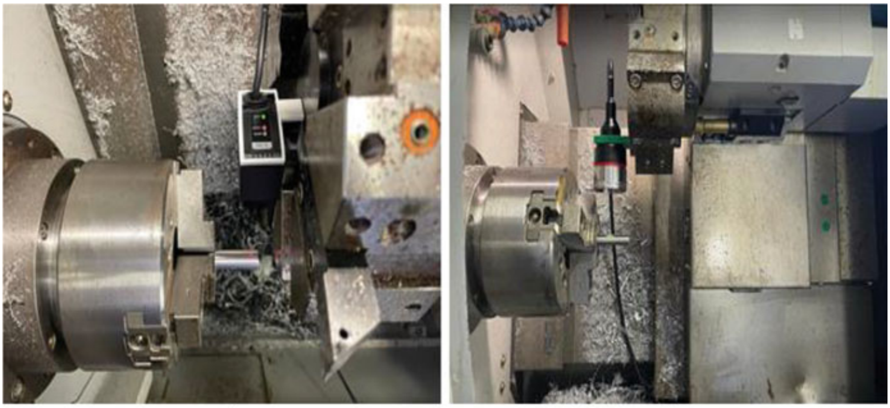


Fig. 6 Figure of the workpiece working zone during the turning process



A B

Fig. 7 Measuring of the diameter deviation by ((**a**) LTS, (**b**) CS)

Fig. 8 Measuring of the diameter with LIEVE micrometer

After the machining, the first TLS was inserted into the tool holder, which we aligned exactly with the center of the workpiece and then defined the zero point at the base of its measuring range (100 mm). In the next step, we divided the sample into 6 sections of 10 mm in length and a circumference of 72 degrees and measured the deviation from the diameter at each section (Fig. 7).

The same measurement principle was used at CS when we reinserted the sensor into the tool holder, set the zero point for CS to (70 mm), and then measured the deviation values from the workpiece diameter. For the purposes of this experiment measuring holders were constructed for both TLS and CS sensors using a 3D printing with Filalab PLA filament.

A LIEVE micrometer with 0–25 mm measuring range and an accuracy of 1 μm were used in this experiment as a standard for the measured values (Fig. 8).

4.1 Experimental Results

Since it was necessary to create custom measurement software for the LTS, the data measured by the LTS was written by the PLC to a text block in the form of measurement time, measurement value, and write index. During the measurement sections, 200 values were measured, from which an arithmetic mean was formed. All data were subsequently processed from text block to Excel program for further analysis (Fig. 9).

In the case of CS, data processing was somewhat easier because Keyence also provides the sensor with software to analyze and process the measurement data, so it was possible to measure more values with one confocal sensor, exactly 1000 measurements per second with an accuracy of 1 μm. The measurement data can be evaluated directly in the CLNavigatorN-N program or exported to Excel (Fig. 10).

As mentioned in the previous part, measured values from the sensor head were saved from the software or PLC to a table in Excel. In Table 1, data of LTS in the form of arithmetic mean values are processed, which were determined from all values for a certain section. In Table 2, data from the same workpiece are processed, but using CS. The last data in Table 3 were processed data measured from micrometer measurements.

The measuring system determines only the zero position deviation, for the real values the following equation must be applied:

$$\Delta_d = l + x \pm y \tag{1}$$

where

Δ_d – real deviation of diameter,
l – measured deviation,
x – the required value,
y – sensor error.

Fig. 9 Example of measured values from LTS

```
00:00.031;55,185;12,336;12336
00:00.046;55,181;12,336;12336
00:00.046;55,169;12,336;12336
00:00.046;55,166;12,336;12336
00:00.046;55,162;12,336;12336
00:00.046;55,158;12,336;12336
00:00.046;55,151;12,336;12336
00:00.062;55,144;12,336;12336
00:00.062;55,139;12,336;12336
00:00.062;55,135;12,336;12336
00:00.062;55,129;12,336;12336
00:00.062;55,123;12,336;12336
```

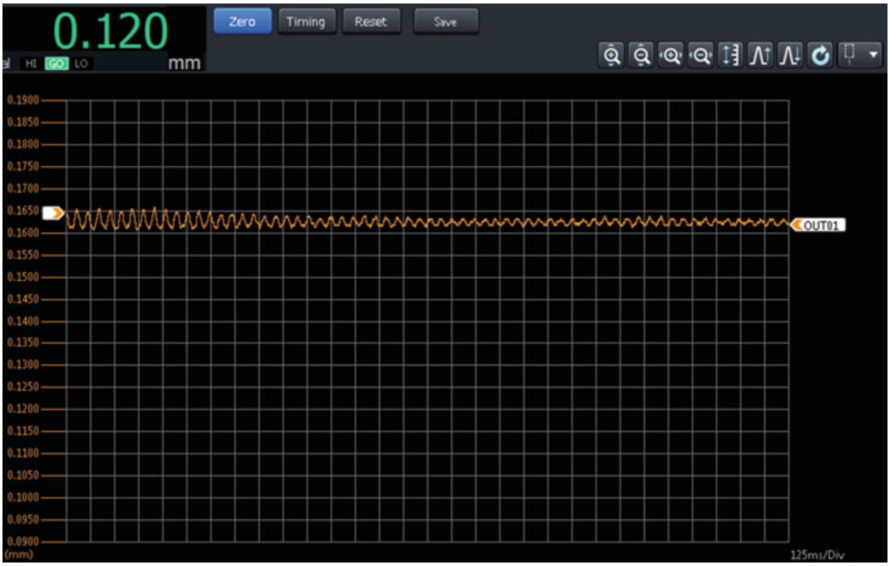


Fig. 10 Example of the measured data from CS in CLNavigatorN-N software

Table 1 Measured data for LTS

Distance	Measured angle of workpiece (°) and deviation in (mm)				
(mm)	0/360°	72°	144°	216°	290°
0	−0.041	−0.069	−0.177	0.099	0.091
10	−0.049	0.002	−0.152	0.034	0.105
20	0.01	0.021	−0.078	0.027	−0.01
30	−0.111	−0.094	−0.022	0.093	**−0.18**
40	−0.03	−0.073	−0.141	0.042	0.089
50	−0.016	−0.021	−0.129	0.036	−0.009

Calculation example of the real measured dimension:

- x: 10 mm,
- l: 0.005 mm,
- y: 0.003 mm,

$\Delta_d = 10{,}005 \pm 0{,}003$ mm.

When measuring the workpiece with both sensors the lowest deviation was about - 0.18 mm and the highest deviation was 0.01 mm, due to the machined surface quality after turning.

From Fig. 11, we can see that the CS is a very accurate representation of the readings from the mechanical micrometer. The largest difference occurred in the 30 mm section, when the difference in the average of the measured values was 0.019 mm. An even greater difference between the LTS readings occurred when

Table 2 Measured data for CS

Distance	Measured angle of workpiece (°) and deviation in (mm)				
(mm)	0/360°	72°	144°	216°	290°
0	−0.041	−0.04	−0.044	0.018	0.015
10	0.03	0.009	−0.018	0.022	0.062
20	0.022	0.029	−0.057	0.088	0.071
30	0.037	0.076	−0.021	0.087	0.071
40	0.032	0.099	−0.026	0.033	0.075
50	0.064	0.026	−0.04	0.011	−0.055

Table 3 Measured data for micrometer

Distance	Measured angle of workpiece (°) and deviation in (mm)				
(mm)	0/360°	72°	144°	216°	290°
0	−0.035	−0.03	−0.039	0.021	0.03
10	0.019	0.096	−0.047	0.001	0.084
20	0.037	0.005	−0.027	0.076	0.081
30	0.025	−0.005	0.052	0.066	−0.02
40	0.02	**0.1**	0.039	0.019	0.11
50	0.063	0.022	0.009	0.008	−0.074

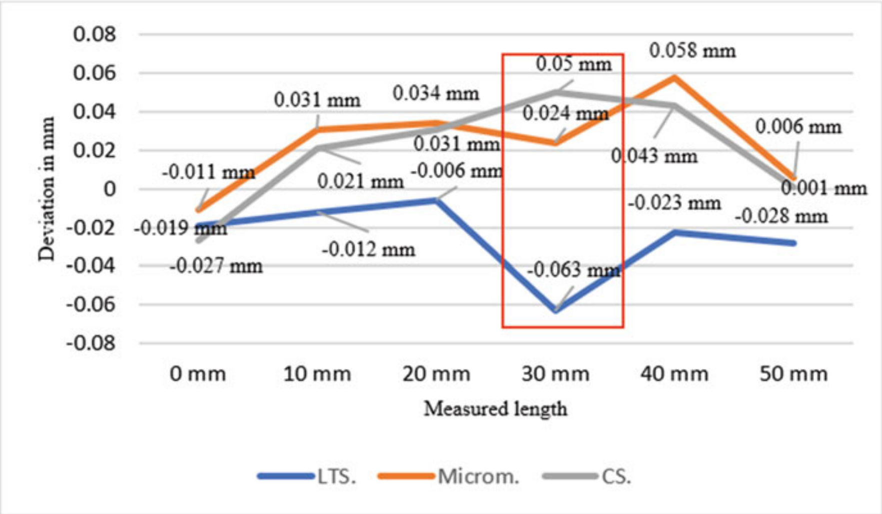


Fig. 11 Graphical comparison of individual measuring systems by deviation of diameter on length

the difference between the mechanical gauge and the LTS exceeded the difference by 0.039 mm, again in the 30 mm section. Regarding the measured values of the circumference of the workpiece from Fig. 12, we can again confirm that CS measured almost identical values as a mechanical gauge, the difference between a

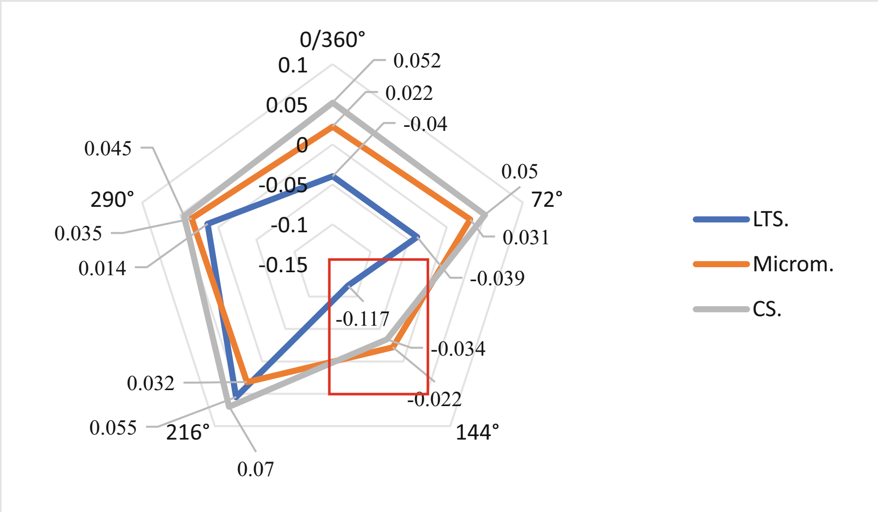


Fig. 12 Graphical comparison of individual measuring systems by deviation of diameter on workpiece angle

mechanical gauge and LTS increased on the contrary. At an angular rotation of 144°, the difference of the measured values reached up to 0.095 mm.

5 Discussion

In this chapter, a new experimental measurement system focused on contactless optical sensors was presented. Analyzing the diagrams, we can see that the average total deviation of the workpiece diameter is between - 0.18 mm and 0.01 mm. Based on these deviations, we can determine the surface errors of the machined material by identifying defectively machined workpieces in turning process. However, these measuring systems also have their limits, namely the measuring distance.

6 Conclusion

From the results of the experiment, it can be concluded that the confocal sensor copied the micrometer measurement data very accurately, with the highest deviation from the measured value being 0.019 mm. This is in contrast to the triangulation sensor, whose deviation from the diameter of the workpiece in comparison with the mechanical micrometer was at one point up to 0.095 mm. With this experiment we have clearly proved that the use of optical sensors has its application in the machine industry, especially in the measurement of surface properties of workpieces after turning.

The second part of research at the Faculty of Manufacturing Technologies in Prešov is the practical implementation of optical sensors in manufacturing operations as a substitute for post-machining quality control. Contactless sensors are one of the best technologies in the field of optical distance and position measurement. A disadvantage of small and medium-sized automated plants is the high purchase price of the device compared to the more common diffuse sensors or single-channel optical sensors, but in large-scale production and advanced production with automation processes, where they belong, where very high measurement accuracy must be achieved, these sensors are essential.

Acknowledgments All authors of the chapter would like to thank the research team of grant agency for the support of research works and the co-financing by the VEGA 1/0268/22 project.

References

1. Mrkvica, I., Neslušan, M., Čep, R., & Sléha, V. (2016). Properties and comparison of PVD coatings. *Tehnički vjesnik/Technical Gazette, 23*(2), 569–574. ISSN 1330-3651.
2. Petrú, J., Zlámal, T., Mrkvica, I., & Čep, R. (2013). The effect of thermal shocks on wear of exchangeable sintered carbide inserts during the cutting proces. *Manufacturing Technology, 14*(4), 590–596. ISSN 1213-2489.
3. Flenger, P., et al. (2019). Processing a measured vibroacoustic signal for rock type recognition in rotary drilling technology. *Measurement: Journal of the International Measurement Confederation, 134*, 451–467. ISSN: 0263-2241.
4. Pitel, J., Matiskova, D., & Marasova, D. (2019). A new approach to evaluation of the material cutting using the artificial neural networks. *TEM Journal - Technology Education Management Informatics, 8*(2), 325–332 ISSN: 2217-8309.
5. Peterka, J., et al. (2020). Modification of cutting tools by drag finishing. *MM Science Journal, 2020*, 3822–3825. ISSN: 1803-1269.
6. Monka, P. P., et al. (2020). Optimal cutting parameter specification of newly designed milling tools based on the frequency monitoring. *International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-020-06169. ISSN: 0268-3768.
7. Monková, K., et al. (2020). Durability and Tool wear investigation of HSSE-PM milling cutters within long-term tests. In *Engineering failure analysis* (Vol. 108) ISSN: 1350-6307.
8. Michalík, P., Zajac, J., Duplák, J., & Pivovarník, A. (2012). CAM software products for creation of programs for CNC machining. In *Lecture notes in electrical engineering, 2011,international conference on future communication, computing, control and management: ICF4C 2011: Pucket: 16–17 December, 2011* (Vol. 141, no. 1, pp. 421–425) ISSN: 1876-1100 ISBN: 978-364227310-0.
9. Suh, Y. (2019). Laser sensors for displacement, distance and position. *Sensors, 19*, 1924. https://doi.org/10.3390/s19081924
10. Kishore, P., Dinkar, D., Shankar, M., Srimannarayana, K., Pachava, V. R., Sengupta, D., & Parne, S. (2011). Non-contact vibration sensor using bifurcated bundle glass fiber for real time monitoring. *Proceedings of SPIE*, 8311. https://doi.org/10.1117/12.904566
11. Blateyron, F. (2011). Chromatic confocal microscopy. In R. Leach (Ed.), *Optical measurement of surface topography*. Springer. https://doi.org/10.1007/978-3-642-12012-1_5

12. Hošek, J., & Linduška, P. (2021). Simple modification of a commercial laser triangulation sensor for distance measurement of slot and bore side surfaces. *Sensors, 21*, 6911. https://doi.org/10.3390/s21206911
13. Knapčikova, L., & Peraković, D. (2022). Innovative approaches in technology challenges in the context of industry 4.0. *Wireless Network, 28*, 427–429. https://doi.org/10.1007/s11276-021-02863-0
14. Knapcikova, L., & Peraković, D. (2021). Challenges of industrial engineering, management and ICT. *Wireless Network, 27*, 1557–1559. https://doi.org/10.1007/s11276-021-02598-y
15. Zhou, Q., Chen, R., Huang, B., Liu, C., Yu, J., & Yu, X. (2019). An automatic surface defect inspection system for automobiles using machine vision methods. *Sensors, 19*, 644.
16. Zbontar, K., Podobnik, B., Povše, F., & Mihelj, M. (2013). On-machine laser triangulation sensor for precise surface displacement measurement of various material types. *Proceedings of SPIE, 8839*. https://doi.org/10.1117/12.2022838
17. Yu, Q., Wang, C., Zhang, Y., Hu, S., Liu, T., Cheng, F., Wang, Y., Lin, T., & Xi, L. (2022). Error analysis and correction of thickness measurement for transparent specimens based on chromatic confocal microscopy with inclined illumination. *Photonics, 9*, 155. https://doi.org/10.3390/photonics9030155
18. Mcgrath, M., Scanaill, N., & Cliodhna. (2013). Sensing and Sensor Fundamentals. In *Sensor Technologies*. Apress. https://doi.org/10.1007/978-1-4302-6014-1_2
19. Zou, X. C., Zhao, X. S., Li, G., Li, Z. Q., & Sun, T. (2017). Non-contact on-machine measurement using a chromatic confocal probe for an ultra-precision turning machine. *International Journal of Advanced Manufacturing Technology, 90*, 2163.
20. Jordan, H.-J., Wegner, M., & Tiziani, H. (1998). Highly accurate non-contact characterization of engineering surfaces using confocal microscopy. *Measurement Science and Technology, 9*(7), 1142–1151.
21. Fu, S., Cheng, F., Tjahjowidodo, T., Zhou, Y., & Butler, D. (2018). A non-contact measuring system for in-situ surface characterization based on laser confocal microscopy. *Sensors, 18*, 2657. https://doi.org/10.3390/s18082657
22. Zhou, Q., Chen, R., Huang, B., Liu, C., Yu, J., & Yu, X. (2019). An automatic surface defect inspection system for automobiles using machine vision methods. *Sensors, 19*(3), 644. https://doi.org/10.3390/s19030644
23. Cheng, F., Fu, S., & Chen, Z. (2020). Surface texture measurement on complex geometry using dual-scan positioning strategy. *Applied Sciences, 10*, 8418. https://doi.org/10.3390/app10238418