DYNAMIC POSITION MEASUREMENT OF THE CNC MACHINE USING LASER INTERFEROMETRY

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Currently, emphasis is placed on the ever-higher accuracy and speed of measuring the geometric accuracy of CNC machine tools. Achieving the highest possible accuracy is often time-consuming, which results in higher financial costs.

The purpose of this study was to verify the suitability of the dynamic measurement of the position CNC machine based on laser interferometry using angular optics concerning static measurement. In the case of both measurements, a commercially available laser interferometer XL-80 was used. First, a static measurement was performed on the horizontal X axis, then a set of dynamic measurements was performed, and the last static measurement was evaluated as a control. The test therefore assesses the accuracy of dynamic position measurement in accordance with ISO 230-2 parameters. The advantage of dynamic measurement is the provision of a more realistic and detailed view of CNC machine tool errors thanks to the high resolution of the measurement itself. At the same time, this research opens another unexplored area of mutual synchronization of data obtained from the CNC machine and data from the reference method.

KEYWORDS

dynamic measurement, static measurement, position deviation, large CNC machine tools, laser interferometry

1 INTRODUCTION

Machine tools are an essential part of the modern production process for machining various materials with ever-increasing precision requirements [Schwenke 2008, Luo 20024], productivity [Sarvas 2024], automation [Bloss 2007], process monitoring, multiaxis machining, IoT integration and other [Soori 2023].

Mechanical accuracy and automation speed are based on design quality, manufacturing accuracy, assembly quality, and control quality. While numerical compensations represent a more cost-effective approach to increasing the geometric accuracy of a machine [Holub 2022, Zhang 1985, Zhang 2023] and working accuracy of the machine [Holub 2020].

New procedures, hardware and software enable developments in measurement techniques. One of the innovative approaches is the so-called on-the-fly measurement [Schwenke 2009] which increases the efficiency and accuracy of data acquisition and analysis. These methods enable adjustments and calibrations in shorter / real time, thereby significantly improving measurement processes [Budzyn 2018, Budzyn 2021, Holub 2017].

Dynamic / continuous measurement is enabled by devices such as XM60 (free run mode) (RENSIHAW, UK), Laser TRACER (on the fly) (Hexagon, SE). These measuring devices are significantly more expensive than the commonly used laser interferometers of the XL-80 type, which are among the most frequently used interferometers by manufacturers and service providers of CNC machine tools.

Interferometric measurements are based on the Michelson principle. The emitted light is divided into two beams depending on the polarization: measurement and reference. A detector in the laser head detects the phase difference with the returning laser beams. Depending on the configuration of the optomechanical components, the measured displacement distance can be applied to calculate various parameters of the machine tool [Budzyn 2021]. Laser interferometry has a wide range of applications in diagnostics and in the case of examining the precision of CNC machine tools [Begovic 2014, Castro 2008, Elmelegy 2023, Lingeswaran 2017, Marek 2023, Zhang 2015].

This article is focused on verifying the possibility of using the XL-80 laser interferometer for dynamic measurements, focused on angular and straightness measurements. In the case of these errors, it is not necessary to know the exact position of the machine axis due to continuous changes in uniform deviations. It is important to describe the position error introduced due to the triggering of the position depending on the method of synchronization of the scanned information from the laser and the position of the machine obtained from the linear encoder of the machine. As a trigger, the signal from the CNC program (asynchronous action) and further via OPC UA communication was tested [Holub 2022], which has a great potential for a rapid data publication [Reddy 2023].

2 DEMONSTRATOR

The position accuracy was performed on the MCV 754 Quick (KOVOSVIT MAS, CZ). It is a three-axis vertical machining centre with a C-frame shape. The machine is equipped with a cross table (axis X, Y) and a spindle (Z) with travel on a stand. The kinematic chain of this machine, from work piece to tool, is W-X-Y-Z. The machine uses a Siemens control system Sinumerik 840D sl. The machine tool has integrated OPC UA (Open Platform Communications Unified Architecture). This integration facilitates real-time monitoring, control and data acquisition across different machine tools.

In the Tab. 1 are shown technical parameters of the milling tool, those are declarable based on the standard ISO 230-2:2014 [ISO 230-2]. The size of the workspace is defined based on the Fig. 1.

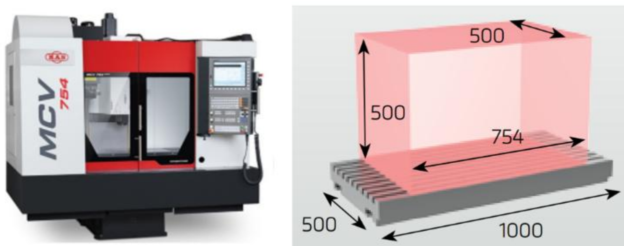

Figure 1. Workspace of the MCV 754 Quick

	Value
Positioning error [mm]	0.012
Positioning repeatability [mm]	0.005
Axis length x/y/z [mm]	754/500/500

Table 1. Selected machine parameters

3 METHODS

The calibration laser XL-80 (Renishaw, UK) based on the principle of laser interferometry is designed to provide excellent stability of measurements and, due to mobility, provides quick diagnostics for checking CNC machine tools. This device provides measurement of various parameters such as measurement of position, straightness, perpendicularity, flatness and so on. The test is based on the principle of angle optics measurement in the X-axis positioning measurement configuration. The measurement uncertainty can be estimated according to the following equation [Renishaw 2013]:

$$U_{(k=2)} = 0.2\ \mu m + 0.3 \times L\ \mu m/m \qquad (1)$$

The geometric accuracy tests of machines refer to the verification of dimensions, positions, and shapes and the mutual movement of components that will affect the accuracy of the machine's work and are defined in [ISO 230-1:2012, ISO 230-2:2014]. Standard measurement based on laser interferometry takes place using a static method, schematic diagram in Fig. 2. The optical assembly consists of a He-Ne laser, an interferometer, and a reflector. The reflector is fixed to the spindle. In the assembly, the interferometer is a moving component fixed to the machine axis in position S (starting point of measurement). From point S, it moves back to position 0 to define backlash. Subsequently, the axis moves and gradually stops for 5 s at predefined distance intervals (16 positions), until it reaches the end at point F. The axis then performs a reverse movement, when, as before, it records the position data at the defined positions for 5 s. The measured position based on laser interferometry was compared with the read position in the machine. A different value in the resulting positions is considered an error.

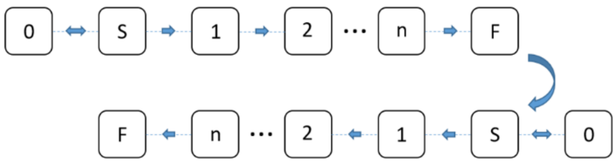

Figure 2. Schematic diagram of the static measurement

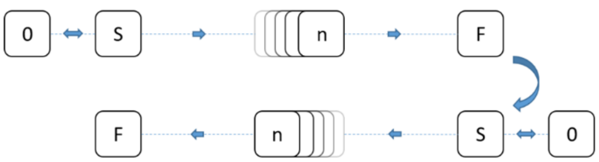

Figure 3. Schematic diagram of the dynamic measurement

On the contrary, dynamic measurement differs from static measurement by continuous data collection. The idea was based on the same concept as static measurement when backlash was defined before cycle measurement. The interferometer does not stop during measurement, the axis was constantly in motion during individual measurements of different axis speeds. Due to software limitations, the data readout sampling frequency had been experimentally determined to be 100 ms. At a lower sampling rate, the commercial laser showed considerable instability. The dynamic measurement scheme is shown in Fig. 3. The measured position based on laser interferometry was compared with the read position in the machine. A different value in the resulting positions is considered an error. And in the end, the time saving between the static and dynamic measurement method was compared.

4 DATA SYNCHRONIZATION

The software applied for external laser control was used through the LabVIEW development environment. Renishaw has released an SDK (Software Development Kit) for this laser control option, which acts as a library that allows direct communication with the laser (functions to connect and disconnect the laser, drivers and read data). Fig. 4. shows a block diagram of the measurement setup connection and a measurement flow chart.

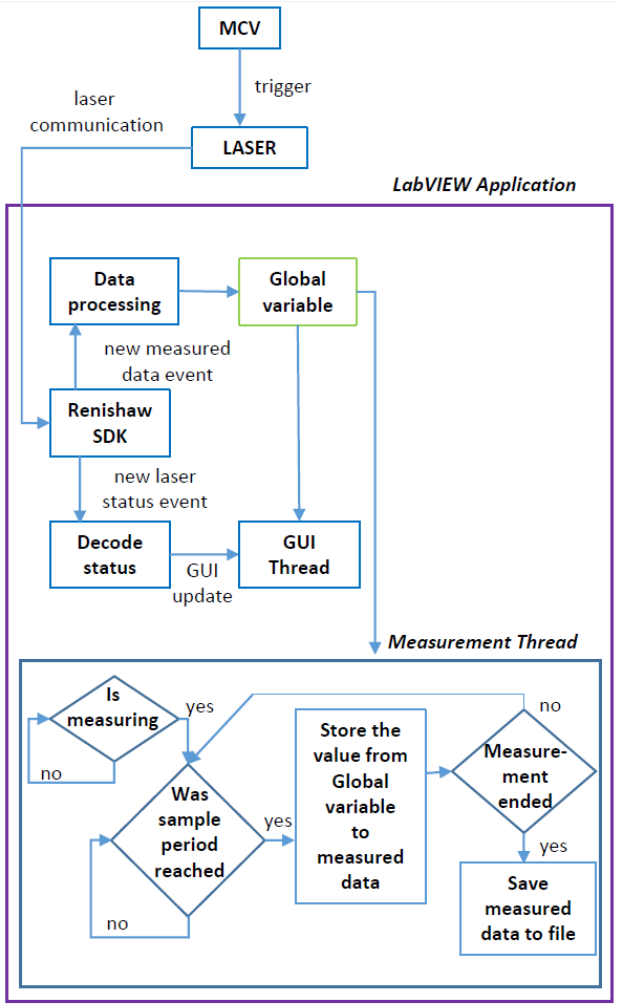

Figure 4. Diagram of the dynamic measurement

The software allows to choose the type of measurement between static or dynamic measurement. It also allows to choose the number of measurement cycles, whereby one measurement cycle means the measured position in the forward and backward directions. Another parameter is the sampling frequency (sample period) of data collection. The triggering of individual cycles itself was defined in the machine tool program. The developed software displays current information about the scanned data in graph form. The horizontal X-axis represents time [s], where the start is t_0 and every other value is +dt (sample period). The vertical Y axis represents the deviation [μm].

In the pilot dynamic measurement, the synchronization of data collection by the laser and the movement of the machine axis was performed manually, where the operator manually turned on the laser measurement and then started the movement of the machine axis. However, this method of synchronization has not been proven due to the effect of the imprecise delay of the movement of the machine axis relative to the start of data collection. And thus, it was not possible to clearly define the exact beginning and end of the measurement cycle based on the reading frequency of the laser. This fact is proven by the results in Tab. 2, where three independently consecutive measurements of M1, M2 and M3 (Position deviation) at axis speeds of 1 000 [mm/min], 3 000 [mm/min] and 6 000 [mm/min] too large deviations of position between individual measurements occur. Fig. 5 shows a comparison of the time record for the evaluation of time savings during dynamic measurement. The position deviation for each axis positioning speed was determined based on the number of data received at each speed of the axis, which is shown in Tab. 2. In this case, it is also necessary to point out that it is not possible to obtain the exact corresponding deviation in a specific position. Deviation can only be assigned to a specific position based on the time trace. Therefore, for the need for a detailed investigation of the deviation of the position, it is necessary to know the exact position of the reading of the measured value with respect to the position of the axis of the machine. To gain awareness of the current state, it is important to obtain information at least every 5 mm.

Axis speed [mm/min]	M1 [μm]	M2 [μm]	M3 [μm]	Number of data [-]	Measurement time [s]
1000	48	42	21	447	447
3000	27	41	36	150	150
6000	38	39	13	76	76

Table 2. Position deviation of pilot dynamic measurement

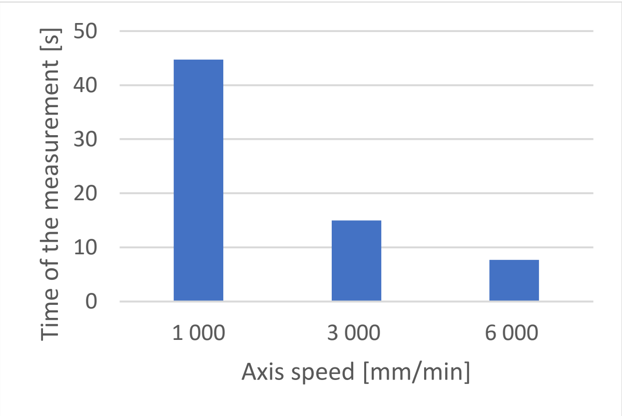

Figure 5. Schematic diagram of time savings during dynamic measurement

The subsequent synchronization of the CNC machine tool and the laser interferometer during the measurement was solved by a signal brought from the digital output of the machine to the input of the laser interferometer. For dynamic measurement, it was necessary to design a method of data collection so that the recording of data from the PC and the positioning of the axis are synchronized, according to scheme, see Fig. 6. A program was written in the CNC machine to position the interferometer (optical component) so that the X-axis moves towards the reflector by 20 mm after starting. At this point, the measurement of the position of the interferometer in the positive direction of the Y axis was started. Acceleration of the movement of the axis to the desired speed during the measurement is neglected due to the noticeably short start-up distance.

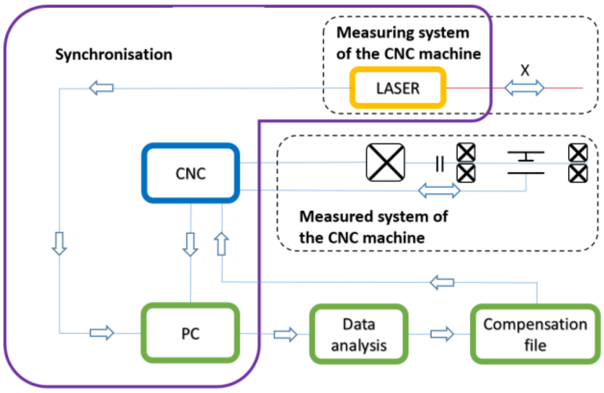

Figure 6. Schematic diagram of data synchronization

Based on this data synchronization, static and dynamic measurements were compared to each other to verify the time savings and deviation value. A static measurement M_S1 was performed first, then three dynamic measurements M_D1, M_D2, and M_D3 with axis feed rates followed of 2 000 [mm/min], 6 000 [mm/min] and 10 000 [mm/min]. At the end of the measurement, a static measurement M_S2 was performed again as a measurement control. The static measurement consisted of five measurement cycles where position values were recorded from sixteen positions. The dynamic measurement was carried out equally in five working cycles, and each cycle is repeated five times, from which the average value is subsequently calculated. The results of the measurements are shown in Tab. 3, 4. The results show that the achieved position accuracy in comparison of both methods turned out in this case to be comparable with a negligible difference. The position deviation in the first static measurement reached a value of 53.1 μm and in the final static measurement 56.6 μm, in both cases the standard deviation is equal to 0.5 μm. Dynamic measurement of the position deviation reached values from 53.60 μm to 55.98 μm. Their standard deviation was on average 0.53 μm in the first and third dynamic measurements, but in the second dynamic measurement it reached a value of 0.80 μm, which could have been caused by the influence of the surrounding environment in the production hall. The advantage is the considerable time saving of dynamic measurement compared to static measurement. A comparable time saving of 35 s is evident in the comparison of static and dynamic measurement in the case of the same axis feed speed of 2 000 mm/min. In the case of a feed speed of 6 000 mm/min, there was a time saving of 109 s, and at a feed speed of 10 000 mm/min, the time saving of dynamic measurement compared to static measurement is up to 124 s.

Axis speed [mm/min]	Nr. of Measurement	Mean position deviation value [μm]	Standard Deviation [μm]	Measurement time [s]
2000	M_{S1}	53.1	0.5	162
	M_{S2}	56.6	0.5	162

Table 3. Results of the static measurement

Axis speed [mm/min]	Nr. of Measurement	Mean position deviation value [µm]	Standard Deviation [µm]	Measurement time [s]
M_{D1} 2000	1	53.60	0.61	127
	2	53.77	0.53	
	3	54.27	0.52	
	4	54.36	0.42	
	5	54.86	0.61	
M_{D2} 6000	6	54.88	0.87	53
	7	57.74	0.95	
	8	54.97	0.84	
	9	55.28	0.66	
	10	55.16	0.69	
M_{D3} 10 000	11	54.97	0.52	38
	12	55.04	0.51	
	13	55.10	0.45	
	14	55.72	0.57	
	15	55.98	0.58	

Table 4. Results of the dynamic measurement

The graph shown in Fig. 7 describes the resulting interval of the position deviation of the dynamic measurement where it compares the results of the static and dynamic measurements as follows. The red points show the mean position deviation values of the first and second static measurements. The interval shown in yellow is defined based on the standard deviation of the resulting position of the static measurement. Dynamic measurements of the mean positions deviation values are shown in blue. Based on their standard deviation, they meet the criterion of occurrence of a value in the static measurement interval. The results of this measurement confirm the ability of dynamic measurement to maintain position measurement accuracy comparably successfully than static measurement.

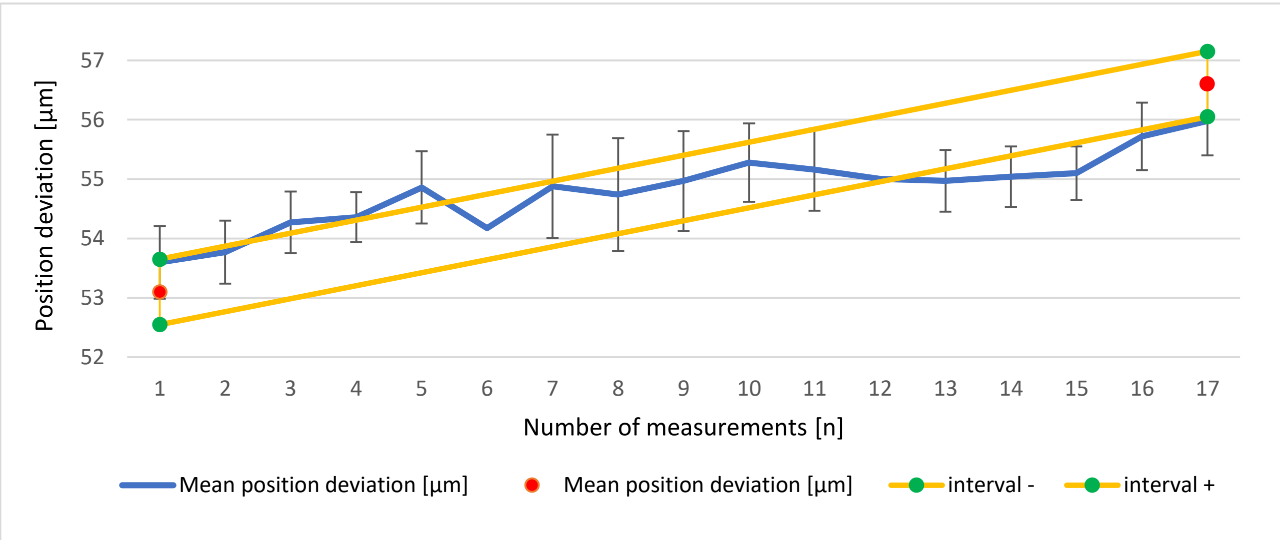

Figure 7. Interval of the position deviation

Of the environmental conditions, it is particularly important to emphasize the effects of temperature fluctuations on the object of measurement, the measuring system and the clamping components. Therefore, during the measurements, the current temperature of selected components of the CNC machine tool was monitored in detail by external sources at individual points of the (mean of 526 values) and compared with the current temperatures obtained directly from the machine before and after the measurement on the X-axis linear scale. The minimum and maximum temperature were also recorded on the X-axis linear scale. It follows from the data that the temperature gradient up to 1°C was not exceeded, therefore the data can be considered valid, see Tab. 5 and 6.

	External source axis X+	External source axis X-
Min T1 [°C]	26.20	26.12
Max T2 [°C]	27.15	26.97
Mean temperature [°C]	26.66	26.97
Standard Deviation [°C]	0.21	0.16

Table 5. Machine axis temperature before and after the measurement at individual points

	Axis X+	axis X-
Temperature before T3 [°C]	26.4	26.4
Temperature after T4 [°C]	27.0	26.7

Table 6. Machine axis temperature before and after the measurement obtained directly from the CNC machine tool

5 DISCUSSION

This study investigated the uncertainty of the dynamic measurement relative to static measurement of position accuracy using a conventional laser interferometer. For this purpose, the synchronization of dynamic measurement data was also investigated using the LabVIEW development environment. While previous studies dealt with the dynamic measurement methodology itself [Budzyn 2021], they have not explicitly focused on determining the dynamic measurement's uncertainty using angle optics. This study proves that the dynamic measurement of the position of the linear axes of the CNC machine using angle optics and the commercially available device XL-80 from the company (Renishaw, UK) is able to compete with the currently standard static measurement not only in measurement accuracy but also in a much shorter time.

The advantage of laser interferometry and its dynamic measurement is a higher sampling frequency based on continuous data collection, as it provides detailed information about the current state of the machine. The laser interferometer provides a suitable sampling frequency for this purpose, even if it reaches the manufacturer's stated sampling frequency of 60 ms, based on testing, a value of 100 ms was determined to maintain the stability of the measurement. However, the main issue remains the synchronization of position data between the CNC machine itself and the laser interferometer. To be able to synchronize the measured data from both entities, it is first necessary to test different communication platforms that will meet the sampling frequency criterion. The subject of testing will be OPC UA platforms (Siemens, DE), where the highest sampling frequency is the same as a laser interferometer – 100 ms. Furthermore, the S7comm protocol (Siemens, DE), which achieves a sampling frequency of 10 ms and the highest sampling frequency possible using Edge Computing in combination with Python. However, further studies are needed to confirm the functionality of the proposed platforms.

6 CONCLUSIONS

The implementation of devices based on the principle of nanotechnology into CNC machine tools to speed up the current methods of measurement processes plays a significant role in this area. Their benefit is obtaining essential information about the behaviour of the CNC machine, able to meet the production requirements regarding machining accuracy.

This article discusses the evaluation of the dynamic measurement of the position accuracy of a CNC machine tool with respect to the current static measurement of the position accuracy. The calibration laser system XL-80 based on the principle of laser interferometry from Renishaw was applied as a measuring device for data acquisition. To verify the initial accuracy of the position, a static measurement was performed, followed by a set of consecutive dynamic measurements. Finally, to verify the accuracy of the position, a final static measurement was performed. Based on both static data, the position accuracy error interval was determined based on the standard deviation, in which the occurrence of dynamic measurement values can be expected. From the conducted study, the comparable time saving of the dynamic measurement is 124 s shorter than the static measurement due to the parameters of the test CNC machine.

The results of the measurements based on the current, static solution and the dynamic result show mutual comparability of the results, therefore a further procedure in solving this problem in the field of large machine tools is assumed, where significant time savings can occur when measuring position deviation. At the same time, thanks to the simplicity of dynamic measurement, its application is a promising benefit for common industrial applications both in the production and in the industrial sphere.

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REFERENCES

[Begovic 2014] Begovic, E., et al. Laser Interferometry – Measurement and Calibration Method for Machine Tools. 3rd Conference "Maintenance 2014", Zenica, Bosnia and Herzegovina, 2014.

[Bloss 2007] Bloss, R. Machine tools become much more than just a lathe or milling machine. Assembly Automation. 2007, Vol. 27, No. 1, pp 9-11. DOI: 10.1108/01445150710724630.

[Budzyn 2018] Budzyn, G., et al. Comparison of Static and Dynamic Laser Based Positioning Methods for Characterization of CNC Machines. Journal of Machine Engineering, 2018, Vol. 18, No. 4, pp 39-46. DOI: 10.5604/01.3001.0012.7631.

[Budzyn 2021] Budzyn, G., et al. Laser interferometer based instrument for 3D dynamic measurements of CNC machines geometry. Optics and Lasers in Engineering, 2021, Vol. 142, s. 106594, ISSN 0143-8166. DOI: 10.1016/j.optlaseng.2021.106594.

[Elmelegy 2023] Elmelegy, A., Zahwi, S. Comparative study of error determination of machine tools. International Journal of Advanced Manufacturing Technology, 2023. Vol. 124, pp 4575–4602. DOI: 10.1007/s00170-022-10358-1.

[Holub 2017] Holub, M., et al. Application on-the-fly measurement of CNC machine tools. MM Science Journal, 2017, pp 2085-2089. ISSN 1803-1269. DOI: 10.17973/MMSJ.2017_12_201791.

[Holub 2020] Holub, M., et al. Experimental Study of the Volumetric Error Effect on the Resulting Working Accuracy—Roundness. Appl. Sci. 2020, 10, 6233. DOI: 10.3390/app10186233.

[Holub 2022] Holub, M., et al. Numerical Aspects of Multilateration for Volumetric Error Calculation. Machines 2022, 10, 833. DOI: 10.3390/machines10100833.

[Holub 2022] Holub, M., et al. Experimental study of operational data collection from CNC machine tools for advanced analysis. 20th International Conference on Mechatronics - Mechatronika (ME), Pilsen, Czech Republic 2017, pp 1-5. DOI: 10.1109/ME54704.2022.9983425.

[Lingeswaran] Lingeswaran, P., et al. Analysis of Position Accuracy Using Laser Interferometer in Vertical Milling Machine. International Journal of Engineering Research & Technology, 2017, Vol. 5, No. 07. ISSN 2278-2018.

[Luo 2024] Luo, X., et al. Parallel Hybrid Control Model of CNC Machine Tool Based on Neural Network and PID Algorithm. Frontier Computing on Industrial Applications Volume 2, 2024, pp 217-222. DOI: 10.1007/978-981-99-9538-7_32.

[Marek 2023] Marek, J., et al. Design and Operation of CNC Machine Tools. 1st edition. (Stavba a provoz CNC obráběcích strojů. 1. vyd.). Prague: MM publishing, 2023. ISBN 978-80-907452-3-0.

[Reddy 2023] Reddy, G., et al. "OPC UA Implementation for Industrial Automation - Part 2: Integrating PubSub Model with TSN," 2023 1st International Conference on Circuits, Power and Intelligent Systems (CCPIS), Bhubaneswar, India, 2023, pp. 1-6. DOI: 10.1109/CCPIS59145.2023.10291682.

[Renishaw 2013] Renishaw. XL-80 and XC-80 Error Budget and Uncertainty Calculations; Renishaw: Wotton-under-Edge, UK, 2013.

[Sarvas 2024] Sarvas, M., et al. Influence of Machine Tool Operating Conditions on the Resulting Circularity and Positioning Accuracy. Machines, 2024, Vol. 12, No. 5, pp 352. DOI: 10.3390/machines12050352.

[Soori 2023] Soori M., et al. Robotical Automation in CNC Machine Tools, A Review. Acta Mechanica et Automatica, 2023, Vol. 18, No. 3, pp 434-450. DOI: 10.2478/ama-2024-0048.

[Schwenke 2008] Schwenke, H., et al. Geometric Error

Measurement and Compensation of Machines—An Update. CIRP Annals: Manufacturing Technology, 2008, Vol. 57, No.2, pp 660-675. DOI: 10.1016/j.cirp.2008.09.008.
[Schwenke 2009] Schwenke, H., et al. On-the-fly calibration of linear and rotary axes of machine tools and CMMs using a tracking interferometer 2009, Vol. 58, No. 1, pp 477-480. DOI: 10.1016/j.cirp.2009.03.007.
[Zhang 1985] Zhang, G., et al. Error Compensation of Coordinate Measuring Machines, CIRP Annals, 1985, Vol. 34, No. 1, pp 445-448, ISSN 0007-8506, DOI: 10.1016/S0007-8506(07)61808-3
[Zhang 2015] Zhang, Y., et al. Research of error detection and compensation of CNC machine tools based on laser Interferometer. 2nd international conference on machinery, materials engineering, chemical engineering and biotechnology, 2015, pp. 285–289. DOI: 10.2991/mmeceb-15.2016.56.
[Zhang 2023] Zhang, Z., at al. Geometric error measuring, modelling, and compensation for CNC machine tools: A review. Chinese Journal of Aeronautics. 2023, č. March. ISSN 10009361.
[ISO 230-2] ISO 230-2-2014, Test code for machine tools, Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes, 2014.

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