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ASSESSING THE PRECISION OF MACHINE TOOLS THROUGH VARIOUS MEASUREMENT SYSTEMS

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Abstract: *Nowadays, machine tools have to meet high precision requirements when it comes to manufacturing parts that have to correspond exactly to the specified geometries. Achieving high precision and accuracy when machining parts is a growing challenge, especially as machine tool operating hours increase. This increasing challenge emphasizes the need for regular verification of machine tool accuracy. In this study, the accuracy of a three-axis milling center was investigated, analyzing different measurement systems suitable for evaluating the precision of machine tools. The main objective was to evaluate the feasibility of using faster and less expensive inspection methods and measurement systems without compromising the reliability of the evaluation process. The research included an investigation of two different measurement systems developed for the acquisition of machine tool accuracy data: a coordinate measuring machine equipped with a contact sensor and a 3D laser scanner. The aim of this comparative analysis is to identify optimal approaches to machine tool accuracy assessment that balance speed and affordability while ensuring the reliability and trustworthiness of the test results obtained.*
Key words: machine tools, accuracy, CMM, 3D laser scanner

Procena tačnosti mašina alatki primenom različitih mernih sistema. *Danas su mašine alatke podložne visokim zahtevima za obradu delova sa strogo odstupanjima od navedene geometrije. Zadovoljavanje ovih zahteva, odnosno postizanje visoke preciznosti i tačnosti u obradi delova, postaje sve veći izazov sa povećanjem broja radnih sati mašine alatke. Iz ovih razloga potrebno je periodično proveravati tačnost alatne mašine. U ovom radu ispitana je tačnost troosnog centra za glodanje i analizirana je mogućnost različitih mernih sistema za ispitivanje tačnosti alatne mašine. Osavremenjavanje analize je utvrđivanje mogućnosti korišćenja bržih i jeftinijih ispitivanja i mernih sistema za proveru tačnosti mašina alatki, bez narušavanja pouzdanosti ispitivanja. Ovo istraživanje obuhvata dva merna sistema za prikupljanje podataka o tačnosti alatnih mašina, i to koordinatnu mernu mašinu sa kontakt senzorom i 3D laserski skener.*
Ključne reči: *mašina alatka, tačnost, CMM, 3D skener*

1. INTRODUCTION

The demands placed on modern machine tools in terms of precision and accuracy have soared to unimagined heights. Therefore, achieving and maintaining precision is a primary goal for designers, manufacturers and users of these tools. However, this quest for higher accuracy is often accompanied by rising machining costs, which can affect manufacturers' competitiveness in the market. To counteract this dilemma, manufacturers traditionally strive to meet minimum customer requirements and keep product prices as competitive as possible.

But in today's world, even these minimal customer requirements for the precision and accuracy of machined parts have skyrocketed. Consequently, there is a compelling need to continuously monitor the precision of machine tools. When procuring or installing a new machine tool in a production system, conducting geometry validations and performance tests is essential to evaluate its accuracy and precision [1]. While there are standardized procedures for such evaluations at initial purchase or installation [2-4], these procedures prove to be time-consuming and expensive for ongoing monitoring of machine tool performance. In the search for faster and more cost-effective methods of testing machine tool accuracy, some researchers have investigated alternative methods of analyzing machine tool performance using different measurement systems [5].

End users of machine tools demand exceptional machining performance. To assess the accuracy of a machine tool, they must therefore test it on a "test workpiece" This assessment is of particular importance for the evaluation of machining centers. After machining, the "test workpiece" is analyzed using various measuring devices, primarily coordinate measuring machines (CMMs), which have a high degree of precision. In addition to CMMs, optical 3D scanners can also be used to evaluate the deviation of the machined workpieces from the nominal geometry [6, 7]. In study [7], five digitization techniques were compared to evaluate their effectiveness and capabilities. The methods involved three variations of a laser scanner, a fringe projection

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system, and an X-ray method. The evaluation comprised obtaining point clouds using diverse approaches: from acquiring an ordered point cloud through a laser integrated into a Coordinate Measuring Machine (CMM) to obtaining a disordered point cloud using a manual laser, tracked with a Krypton Camera. Furthermore, the assessment included an Exascan manual laser with targets, an ordered point cloud obtained via high-precision Computerized Tomography (CT), and an Atos fringe projection scanner with targets. Each digitization system also incorporated specific Reverse Engineering (RE) tools—such as Focus-Inspection, Metris, Vxscan, Mimics, and Atos—to transform the point clouds into meshes for further analysis and utilization. Through this comprehensive comparison, insights were gained into the strengths, weaknesses, and potential applications of each digitization technique across various contexts, offering valuable guidance for future digitization endeavors and industrial uses. Despite their advantage in the speed of data acquisition compared to CMMs, optical 3D scanners are less dominant due to their lower accuracy.

Kortaberria et al [8] evaluated the measurement uncertainty of optical 3D scanners by comparing the results of a coordinate measuring machine and an optical 3D scanner when measuring a "test workpiece" Mendricky [9] emphasizes the speed advantage of optical 3D scanners, but also acknowledges potential disadvantages in precision and accuracy, focusing on analyzes of prismatic parts with an emphasis on edges and small diameter holes. Giganto et al [10] investigated the advantages and limitations of five optical measurement systems for the evaluation of dimensional and tolerance deviations in parts manufactured using additive technology and determined reference parameter values using a coordinate measuring machine.

The aim of this study is to analyze the feasibility of using optical measurement systems to evaluate the accuracy of machine tools and to take advantage of their fast data acquisition of machined workpieces. Optical measuring systems offer a significant advantage in the speed of data acquisition compared to contact measuring systems. To achieve this goal, a "test workpiece" was checked for its dimensions and geometric properties using both contact methods using a coordinate measuring machine and non-contact methods using a 3D laser scanner. By comparing the results obtained with these two methods, conclusions were drawn regarding the suitability of 3D laser scanners for testing the accuracy of machine tools.

2. MATERIALS AND METHODS

Since the aim of this work is to test the accuracy of the machining center for milling, the "test workpiece" was a prismatic part with characteristic shapes produced on three-axis machining centers. The model of the "test workpiece" is based on the model of the test model from the ISO 10791-7 standard, but simplified in order to speed up the test procedure. The test model with the specified characteristic dimensions and geometric features is shown in Fig. 1.

The part was machined on an EMCO ConceptMill450 vertical machining center, where the accuracy was tested. The main spindle of the machining center has a power of 11 kW and the maximum spindle speed is 12,000 rpm. The machining center has a working area of 600x500x500 mm. Three different cutting tools were used to machine the workpiece, namely a face milling cutter with a diameter of 50 mm, an end mill with a diameter of 10 mm and a drill with a diameter of 10 mm. The material of the workpiece is the aluminum alloy AW 6060.

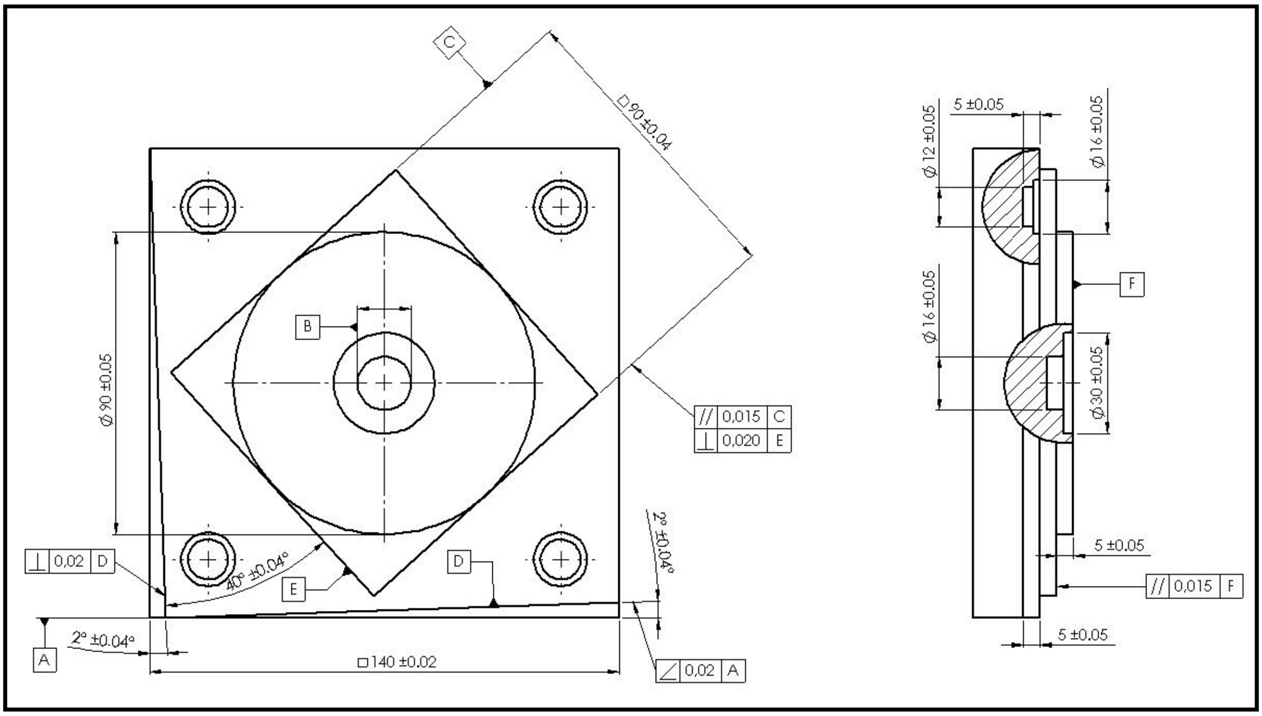


Fig. 1. Machine tool part

The geometric inspection of the test object involved two primary instruments: the CMM Carl Zeiss Contura G2 RDS equipped with a contact measuring sensor (as illustrated in Figure 2) and the 3D laser scanner MMDx100 integrated into the Nikon MCAx+2.0 measuring arm (as depicted in Figure 3). The CMM's metrological performance, outlined in Table 1, showcases its capabilities. In point-by-point measurement mode, the CMM boasts a maximum allowable error for dimensional measurements at 1.8+L/300 µm, while the error reduces to 3.5 µm in scanning mode. The sensor's maximum permissible error stands at 1.8 µm, underscoring its precision in capturing measurements. Conversely, the 3D laser scanner's metrological performance, as detailed in Table 2, presents distinct characteristics. This scanner has an accuracy of 10 µm, which speaks for its precision in capturing dimensional data. However, when used in combination with the articulated measuring arm by hand, the accuracy drops slightly to 48 µm. Nevertheless, the scanner has a commendable resolution of 65 µm, which allows for detailed data capture, as well as a high maximum scanning frequency of 150 Hz, which ensures efficient and fast data capture. The specifications highlight the distinct yet complementary strengths of both instruments – the Coordinate Measuring Machine (CMM) excels in precise and meticulous data capture, while the 3D laser scanner offers rapid and efficient data acquisition, albeit with a slightly reduced accuracy in certain application contexts.

Fig. 2. Coordinate measuring machine Carl Zeiss Contura G2 RDS

Fig. 3. MMDx100 laser scanner integrated with Nikon MCAx+2.0 measuring arm

CMM Carl Zeiss Contura G2 RDS	
Maximum allowable length measurement error	MPEE=(1,8+L/300) µm
Maximum allowable sensor error	MPEP=1,8 µm
Maximum allowable error in scan mode	MPETHP=3,5 µm

Table 1. Characteristics CMM

MMDx100	
Accuracy	10 µm
Min. point resolution	65 µm
Max. frame rate	150 Hz
Stripe width	100 mm
Max. points per stripe	1000
Accuracy comb. with MCAx arm	48 µm
Light source	1 laser crosses

Table 2. Characteristics of the 3D laser scanner

3. RESULTS AND DISCUSSION

The comprehensive analysis of the dimensional and geometric characteristics of the "test workpiece" resulting from the application of the specified coordinate measurement systems is summarized in Table 3. This analysis serves as a pivotal point to evaluate the validity of using optical coordinate measuring systems to test the accuracy of machine tools. It is important to note that this analysis focuses primarily on dimensional and geometric aspects and does not take into account other influencing factors.

The tabulated results in Table 3 provide a detailed breakdown of the measurements taken using the Carl Zeiss Contura G2 RDS CMM and the MMDx100 3D laser scanner integrated with the Nikon MCAx+2.0 measuring arm. The measurements include various dimensional parameters and geometric features of the test workpiece.

These results form the basis for evaluating the potential feasibility and effectiveness of using optical coordinate measuring systems, in particular the 3D laser scanner, in assessing the accuracy of machine tools. While this analysis focuses exclusively on dimensional and geometric features, it lays the foundation for a comparative study of the capabilities of contact and non-contact measurement systems in evaluating the accuracy of machine tools.

The exclusion of other influencing factors in this analysis highlights a specific aspect of measurement accuracy and data acquisition to shed light on the suitability of optical coordinate measuring systems for such evaluations. Further factors could be considered in subsequent assessments to provide a more comprehensive evaluation of the applicability of these measurement systems in assessing machine tool accuracy. The specified tolerances and their differences were adopted on the basis of the recommendations of the

ISO 10791-7:2014 standard. In addition, the requirements that the observed machine tool should meet were taken into account when defining the tolerances. Slightly higher tolerance values were assumed for positions and shapes for which more complex interpolations are required during production.

When performing the machine tool setting accuracy test and carefully examining the results obtained from the experiment (see Table 1), there is a clear discrepancy between the measurements obtained with the contact method using the coordinate measuring machine and the measurements obtained with the non-contact method using a laser scanner. This discrepancy particularly affects numerous observed features that violate the given specifications and exceed the tolerance limits. Consequently, these results cast doubt on the suitability of the machine tool in terms of accuracy.

Remarkably, the coordinate measuring machine with its significantly higher accuracy, which serves as a benchmark (as derived from the metrological performance of the measurements acquired with the contact method), appears to meet all the analyzed accuracy parameters. However, the measurements taken with the laser scanner show a different picture. They reveal a significant number of features that do not meet the specified tolerances, leading to the conclusion that the machine tool is inadequate in terms of accuracy.

The discrepancy in the parameters analyzed, due to the divergence between the results of the different coordinate measuring systems, primarily highlights the unreliability of the laser measurement systems, especially when checking the features against the corresponding specifications. The graphical representation in Figures 4 and 5 illustrates the divergence in orientation tolerances and dimensional characteristics between the observed systems.

No	**Characteristic**	**Nom. value [mm]**	**± Tol.**	**CMM [mm]**	**Dev. CMM +/- [mm]**	**In toler. yes/no**	**LS [mm]**	**Dev. LS +/- [mm]**	**In toler. yes/no**
1	Perpendicular	0	0.02	0.0065	0.0065	Yes	0.044	0.044	No
2	Tilt	0	0.04	0.039	0.039	Yes	0.055	0.055	No
3.1	perpendicular	0	0.02	0.0085	0.0085	Yes	0.087	0.087	No
3.2	Parallelism	0	0.015	0.0092	0.0092	Yes	0.091	0.091	No
4	Parallelism	0	0.015	0.0082	0.0082	Yes	0.091	0.091	No
5	Cylinder diameter	90	0.05	90.041	0.041	Yes	90.009	0.009	Yes
6	Angle	2	0.04	1.962	-0.038	Yes	1.974	-0.026	Yes
7	Length	140	0.02	139.993	-0.007	Yes	139.933	-0.067	No
8	Angle	40	0.04	40.0056	0.0056	Yes	40.017	0.017	Yes
9	Length	90	0.04	90.04	0.04	Yes	90.03	0.03	Yes
10	High	5	0.05	4.994	-0.006	Yes	4.975	-0.025	Yes
11	High	5	0.05	5.0082	0.0082	Yes	4.975	-0.025	Yes
12	Diameter of hole	30	0.05	29.9619	-0.0381	Yes	29.94	-0.06	No
13	Diameter of hole	16	0.05	15.9612	-0.0388	Yes	15.956	-0.044	Yes
14	Diameter of hole	16	0.05	15.9562	-0.0438	Yes	15.93	-0.07	No
15	Diameter of hole	12	0.05	11.9637	-0.0363	Yes	11.967	-0.033	Yes
16	Diameter of hole	5	0.05	5.008	0.008	Yes	4.96	-0.04	Yes

Table 3. Results of the analysis of variance

This unreliability of the laser measurement systems is due to their methodological subtleties and the limitations of the system in terms of accuracy. One of these limitations is the need to apply powder to the workpiece during scanning to reduce reflection, a factor that contributes to the observed variations in measurements.

Considering the strict specifications for evaluating machine tool accuracy, which require minimal deviations and tight tolerances, the laser scanner appears unreliable and insufficient for evaluating the accuracy of machine tools with a "test workpiece" due to the deviations it produces compared to the coordinate measuring machine.

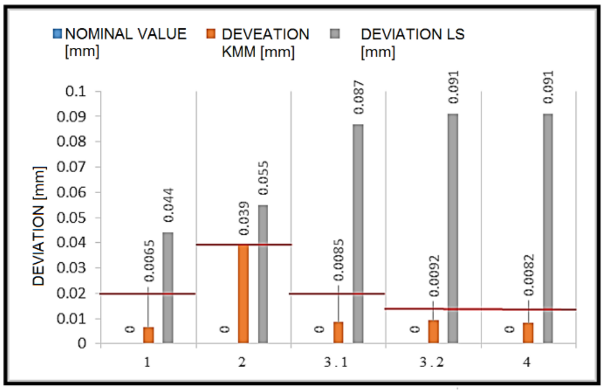
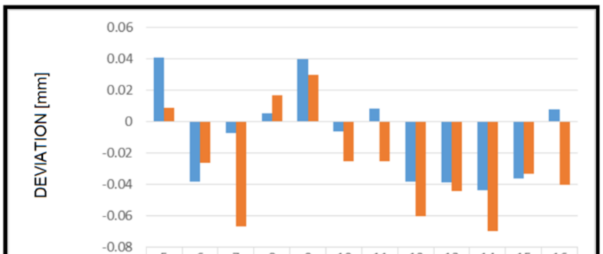


Fig. 4. Deviations for orientation tolerances



	5	6	7	8	9	10	11	12	13	14	15	16
DEVEATION KMM [mm]	0.041	-0.04	-0.01	0.006	0.04	-0.01	0.008	-0.04	-0.04	-0.04	-0.04	0.008
DEVIATION LS [mm]	0.009	-0.03	-0.07	0.017	0.03	-0.03	-0.03	-0.06	-0.04	-0.07	-0.03	-0.04

Fig. 5. Deviations for dimensional characteristics

4. CONCLUSIONS

In view of the high requirements for accuracy and precision in machining, it is important to regularly check whether the machine tools meet these standards over their entire service life. This study investigated whether it is possible to check the accuracy of a machine tool with two different measuring systems using a specific "test workpiece"." The analysis showed that the observed machine tool met the predefined accuracy criteria. The advantage of non-contact measuring systems is that they can capture the required data quickly. However, due to specific application and accuracy limitations, they may not be suitable for analysing parameters with strict specifications compared to CMMs equipped with contact measurement sensors. The MMDx100 laser scanner, a non-contact measurement system considered in this analysis, was deemed unsuitable for accurately assessing the accuracy of machine tools through measurements on "test workpieces".

Future analysis on this topic should investigate the suitability of other non-contact measurement systems, particularly newer generation systems with improved accuracy, to determine if they meet the required characteristics for machine tool accuracy assessment.

5. REFERENCES

[1] Lopez, L.N.L., Lamikiz, A. Mavhine Tools for High Performance Machining. British Library Cataloguing in Publication Data, Springer, 2009. doi: 10.1007/978-1-84800-380-4

[2] ISO 230-2:2014. Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes.

[3] JIS B 6201, 93rd Editon, 2012. MACHINE TOOLS – RUNING TESTS AND RIGIDITY TESTS – GENERAL REQUIREMENTS

[4] ASME B5.54 – 2005 (R2020). Methods for Performance Evaluation of Computer Numericalla Controlled Machining Centres.

[5] Barnfateher, J.D., Goodfelow, M.J., Abram, T. Photogrammetric measurement preocess capability for metrology assisted robotic machining. Measurement, 78, 29 – 41, 2016. http://dx.doi.org/10.1016/j.measurement.2015.09.045

[6] Ramos, B.B., Santos, E.U. Comparative study of different digitization techniques and their accuracy. Computer – Aided Design, 43, 188 – 206, 2011. 10.1016/j.cad.2010.11.005

[7] Radomir, M. Apect Affecting Accuracy of Optical 3D Digitalization, MM Science Journal, March 2267, 2018. 10.17973/MMSJ.2018_03_2017106

[8] Kortaberria, G., Mutilba, U., Gomez, S., Ahmed, B. Three-Dimensional Point Cloud Task-Specific Uncertainty Assessment Based on ISO 15530-3 and ISO 15530-4 Technical Specifications and Model-Based Definition Strategy. Metrology, 2, 394 – 413, 2022. https://doi.org/10.3390/metrology2040024

[9] Radomir, M. Analysis of Measurement Accuracy of Contactless 3D Optical Scanners. MM Science Journal, October 711, 2015. 10.17973/MMSJ.2015_10_201541

[10] Giganto, S., Martinez-Pellitero, S., Cuesta, E., Meana, V.M., Barreiro, J. Analysis of Modern Optical Inspection Systems for Parts Manufactured by Selective Laser Melting. Sensors, 20, 3202, 2020. 10.3390/s20113202

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