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Impact of measurement conditions and measurement strategy on the positioning accuracy and repeatability of the milling plotter

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ABSTRACT

The paper presents the test results of the accuracy and repeatability of the three-axis milling plotter with the use of the LSP 30 Compact laser interferometer. The experiment was carried out using two measurement strategies. A machine learning (ML) model was developed using feed rate v_f and the positioning accuracy and repeatability parameters (A, $A\uparrow A\downarrow$, R, $R\uparrow R\downarrow$, B and $\overline{B}$). Due to the nature of the data, a linear regression model was chosen. A less efficient but more accurate measurement strategy was the ´pilgrim´ strategy. Whereas, the linear measurement strategy proved to be more efficient but less accurate. High, constant insolation of the test stand and air humidity influenced the measurement results. The predicted positioning accuracy and repeatability parameters were determined on the basis of the developed model using first-degree regression equations. Prediction of positioning accuracy parameters depending on measurement conditions and measurement strategies can be a useful tool to control or predict the process machine accuracy and the shaped contour accuracy.

Keywords: positioning accuracy and repeatability, measurement strategy, laser interferometry

INTRODUCTION

A main aspect in assessing the dimensional and shape accuracy of a part is the accuracy of a CNC machine tool. Accuracy test of numerical machine tools are based i.a. on the use of laser systems that enable accurate measurements. The paper [1] discusses one of the methods of measuring machine tools with the use of laser triangulation technology. Laser triangulation measurement is a laser method of optical displacement detection. The advantages of this method are: the possibility of the fine tuning depending on the machined roughness surface, controlled signal processing, minimization of machine tool errors related to additional handling. The disadvantage of this method is that laser displacement sensors are subject to a measurement error similar to the noise that comes from a spot in the reflected laser beam, affecting the measurement accuracy. In addition, the authors presented the factors influencing the measurement accuracy with a laser sensor. These factors included i.a. error due to triangulation method, machine geometry error, position calibration error, environmental evaluation error, ignited measurement route (linear, identifiable or normal).

Another main factor influencing the accuracy of a laser interferometer measurement is temperature. In the paper [2], the authors describe a research methodology detecting errors in the thermal positioning of the linear axis of a machining centre with the use of a laser interferometer. These errors are seen as consequences of geometrical and thermal errors generated due to manufacturing and assembly inaccuracies. The authors of the paper proposed an approach to separate the thermal positioning errors of the machining centre linear axis on the basis of which a predictive model of positioning error model was formulated. After conducting research and analysing the results it was found that the maximum thermal positioning errors of the Z axis in the cold and warm states were reduced for 87.09% and 49.87% after the compensation module was activated. The authors of the paper

[3] have developed an overview of machine tool calibration technologies. The review discusses measurement methods, modelling theories and strategies for compensating for machine tool errors. The most commonly used method for identifying these errors is to use a heterodyne laser system where the wavelength of the laser light provides a traceable reference of the wavelength. The authors of the paper noted that an alternative to interferometric laser multilateration is use of the GPS systems. To compare the performance of the measurement methods, the results of the GPS measurement were compared with the results of the laser tracker measurement. The GPS sensor deviation error was observed which significantly affected the measurement uncertainties. Comparative studies have shown that the GPS technology need to be improved and interferometer systems are still one of the most accurate methods of calibrating machine tools.

The article [4] presents a method for identifying and compensating geometrical errors of a three-axis machining centre based on volumetric measurements of oblique error and positioning error. A geometric model was created and then the principle of laser tracker measuring error was established. The results of experimental studies showed that the method of errors identification and compensation is effective in reducing the volumetric errors of oblique errors. Moreover, the final volumetric diagonal positioning error was controlled at about 20 μm.

Laser systems, used for CNC machine tools calibration are also used in positioning studies of industrial robots. To monitor the final deviations of the robot, the authors of the paper [5] used laser tracker and the GPS system. The research shows that the laser tracker proved to be more accurate system due to the best sampling rate and measurement accuracy. The GPS system appeared to be an inaccurate due to a position error of 380 μm.

Due to the high performance, wide working range and high flexibility, industrial robots are being increasingly used in the automotive, machining or aerospace industries. Whereas, the low positioning accuracy, resulted from the serial configuration of industrial robots, has limited their further developments and applications in the field of high requirements for machining accuracy, e.g., aircraft assembly. Therefore, the authors of the work [6] proposed a neural network-based approach to improve the robots positioning accuracy. The test results showed that all errors were compensated more than from 1.5 mm to 0.5 mm and the robot's accuracy increased by more that 77%.

The paper [7] presents research on the volumetric positioning accuracy of multi-axis CNC machine tools using a laser measurement system. The volumetric accuracy of machine tools was significantly improved. Machine tool accuracy design methods now include a robust design method for machining accuracy and static geometric accuracy. A robust machining accuracy design methods is based on the effective evaluation of the machine tools volumetric positioning accuracy, and the geometric error elements are used as analytical variables without directly directing tolerance calculations. Experimental studies were based on volumetric accuracy modelling, identification of geometrical errors elements for the motion axis, tolerance modelling and a method for designing the machine tool static geometrical accuracy. The results of the study show that the consideration and implementation of the research assumption improved the volumetric positioning accuracy of a multi-axis CNC machine tools.

The work [8] presents a method of compensating for the positioning error of the five-axis machine tools with the use a laser interferometer. In addition, the relationship between thermal error and axis positioning error was investigated. The sold preparation of the test stand increased the accuracy of the obtained measurements. The factors influencing the measurement were: the laser interferometer uninterrupted operation for 9 hours, shorter head run setting, air pressure and humidity. The measurement results showed that the machining error was reduced by more than 85% and 37 % with the current error compensation compared to the lack of traditional error compensation.

The article [9] presents a method of increasing the positioning accuracy of feed kinematic joints. The authors distinguish two groups of errors sources in the positioning machine tools: external and internal sources. External sources of error include ambient temperature, machine components gravitation forces, vibration generated by neighbouring machines. On the others hand, internal sources are inaccuracies in the internal structure of the machine tool as well as geometric and kinematic errors. The authors proposed a method for correcting machine tool positioning errors based on an innovative device to which the measurement of the machine axis can be referred. This device is made of an aluminum body on which five rails are attached.

This device measures machine tool errors at 125 point. The advantage of this method was that it provided improved positioning accuracy throughout the entire machine tool working area and fast accurate measurement.

The paper [10] shows research on the impact of positioning accuracy given by the CNC machine tool encoder. This research focuses on the impact caused by non-compliance with the Abbe principle on the positioning accuracy of the machine tool kinematic coupling, both at idle and trial work. After analysing the measurement results it was concluded that the encoder position in relation to the guides plays an important role. Other condition that depend on the rigidity of the guiding system are the system type (direct or indirect) and the rotation torque reduction. Due to the fact that the sliding conditions on the controlled axis are variable, the application of the Abbe principle is impossible for the correction introduction to improve the positioning accuracy. The authors emphasized what to pay attention to during future research – the ball position in relation to the guide guides and the resultant force of slip resistance; correct selection of the encoder position in relation to the measurement direction and the guides use with appropriate rigid and low friction coefficient.

The work [11] presents the results of research on the adjustment of machining accuracy on long-axis CNC machines in order to increase the positioning accuracy taking into account the effect of thermal expansion. A laser interferometer was used in the *X*-axis study. And the results showed that the *X*-axis positioning accuracy values increased after compensating for the error.

The compensation of positioning errors using a laser interferometer for the Cartesian multi-axis system (MAS) is presented in work [12]. Measurements were made of geometrical and thermal errors constituting the positioning error. It was found that error compensation with a laser measuring system improved the accuracy of the machine by more than 90%, thereby reducing the maximum volumetric error. A study emphasized that all tests were performed at low speed values due to a higher accuracy of measurements.

In the paper [13] the problem of measurement errors in bidirectional linear positioning of a three-axis numerical milling machine was investigated. The results obtained for three linear axes *X, Y* and *Z* with a laser interferometer were reported. An important aspect of the study was that the obtained results were compared with the data specified in the ISO 10791-4 standard: Conditions for testing machining centres – part 4: Accuracy and repeatability of positioning in linear and rotary axes.

In a study [14], errors of linear and angular (pitch) displacement as well as straight-line travel errors for numerical lathes and milling machines were examined using a laser measuring system. According to this paper, for the proper measurement of machine accuracy, attention should be paid to several factors, including the type of machining process, preload, hysteresis of ball and nut mechanisms, positional stability, encoder efficiency, resonance characteristics of drive motors, spindles and other systems, as well as stability and interpolation accuracy. The use of laser systems enables operation under workshop conditions. However, it is worth emphasizing that the proper selection of a measuring system must take into account many important factors, such as purpose, machine type, desired accuracy and precision, place of the machine in the production process, available time, price and maintenance costs of the machine.

The diagnostics of CNC lathe and milling machine with an *XL80* laser interferometer and a weather station comprising temperature, humidity and pressure sensors is investigated in paper [15]. The linear and angular positioning of machine tools in the *X*, *Y*, *Z* axes was measured. The authors emphasized that incorrect movements of the laser head could change laser optics, which might, in turn, be a very time-consuming solution. Consequently, this would lead to repeating measurements in individual axes, whereas any change in the position of the laser or its optics would require calibrating the entire measuring system.

A study [16] deals with the evaluation of the accuracy of positioning of a numerical machine. A laser interferometer was used to measure the accuracy of positioning the numerical lathe in the *X* and *Z* axes, and the QC-10 Ballbar test was employed for general diagnostics of the machine tool. It was found that the *Z* and the *X* axis clearance, reversal errors and radial clearance had the greatest impact on the accuracy of positioning. On the other hand, periodic deviations along with deviations from perpendicularity and straight line as well as following errors had the smallest impact. According to this paper, the backlash can be observed as variations in motion radius deviation outside or inside the arc being performed. This can result from the backlash in the drive system of the machine tool or in the measuring system or from insufficient rigidity of these systems. In order to determine the error values for a machine, it is necessary to refer the results to relevant standards. When analysing the causes of inaccuracies, it can be observed that the easiest way to prevent them is to use compensation of the machine tool control system, and thus to re-implement the accuracy of positioning and diagnostic tests of the machine tool.

A study [17] investigates the impact of compensation of CNC machine geometrical errors on the accuracy of mapping motion with circular interpolation. The results of accuracy and repeatability of positioning for a three-axis numerical milling machine using a laser interferometer were reported. It was emphasized that the main source of positioning errors were geometrical inaccuracies of the machine tool. These inaccuracies resulted from incorrect geometries of the machine tool components. Therefore, to obtain more accurate measurement results, temperature, pressure and air humidity were changed.

The paper [18] presents examples of laser measurement systems used for determining the accuracy and repeatability of positioning of CNC machine tools, emphasizing that machine tool control was a crucial factor in improving the cutting process, increasing product quality and process productivity. The quality of components produced on a CNC machine largely depends on its geometrical and kinematic accuracy.

A study [19] investigates the kinematic accuracy of a three-axis lathe and thread grinder using a laser interferometer. The dynamic calibration of these machines was discussed. The results showed that the errors of lathe positioning repeatability were so serious that they exceeded the values recommended by the ISO standard. This means that the dynamic accuracy of the lathe was incorrect. It was emphasized that the static calibration of lathe positioning accuracy was insufficient for effective assessment of the accuracy of this machine. This demonstrates that both dynamic and static accuracy of positioning machine tools is essential to obtain expected results, and that studies on the accuracy of machine tools are of vital importance.

The aim of this study is to investigate the impact of the measurements conditions and the measurement strategy on the positioning accuracy and repeatability of the three-axis milling plotter.

MATERIALS AND METHODS

Methodology

The object of the study was the three-axis CERTUS milling plotter. Its accuracy and repeatability of positioning in the Y axis were measured, particularly the bidirectional accuracy of positioning A of a numerically controlled axis A, unidirectional accuracy of positioning of an axis ($A\uparrow$ and $A\downarrow$), unidirectional repeatability of positioning ($R\uparrow$ and $R\downarrow$), and reversal value of an axis B. The measuring length l_p was 1500 mm. In accordance with the ISO 230-2 standard and the specified measuring length value, 11 measurement points were selected. Values of the parameters were measured with a step of 150 mm between the measurement points. The study was conducted using two different measurement strategies. The ambient temperature was 24°C and the air humidity was 45%. The tests were performed with the use of the following:

- LSP 30 Compact laser interferometer,
- two linear reflectors, one of which was connected to the tool head while the other was attached to the machine table.

The measuring length was selected based on the range of Y axis movement. The research plan for assessing the accuracy and repeatability of positioning a three-axis CNC milling plotter is shown in Figure 1. The input parameters were measurement strategies and feed motion speed v_f. The output values were accuracy and repeatability of positioning of a milling plotter. The number of measurement points was maintained constant, while the following were made variable: temperature, pressure, air humidity, laser head vibration, and laser interferometer resolution.

The milling plotter is equipped with a PikoCNC5.0 control system and has the maximum spindle speed of 18000 rpm. The maximum travel of the plotter spindle is 1000 mm for the X axis, 2000 mm for the Y axis and 200 mm for the Z axis. The test stand is shown in Figure 2.

Technical parameters of the laser interferometer are listed in Table 1.

Figure 3 shows the strategies applied for measuring plotter spindle motion using the feed speed range v_f = 1000–5000 mm/min. Figure 3a shows the linear strategy and Figure 3b shows the ′pilgrim′ strategy.

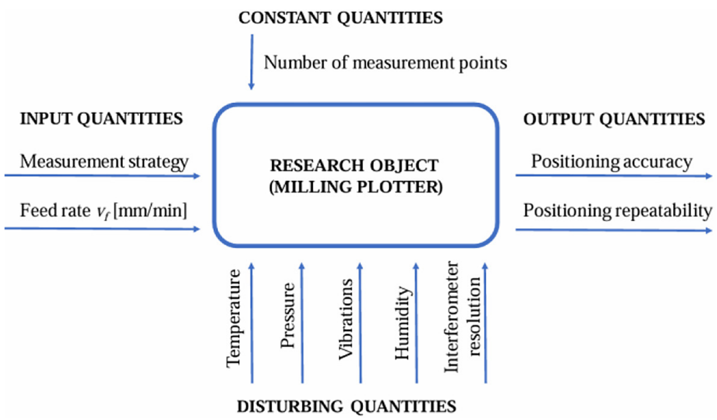

Figure 1. Research plan for assessing the accuracy and repeatability of positioning a three-axis CNC milling plotter

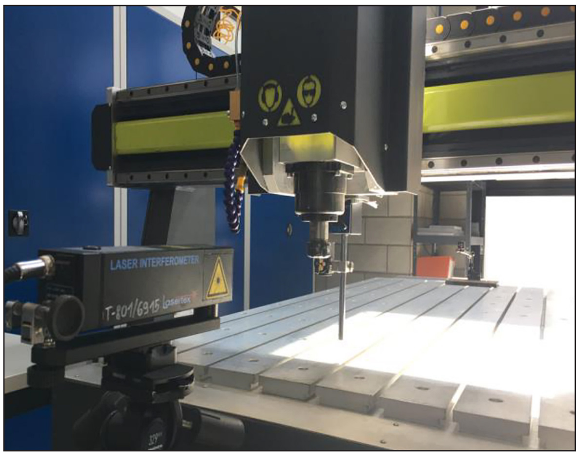

Figure 2. Test stand

RESULTS AND DISCUSSION

The error of positioning milling plotters consists of many factors. This section provides information about the sources of errors regarding the accuracy and repeatability of positioning of the milling plotter (Figure 4). Factors from three groups of measurement errors were taken into account when calculating the accuracy and repeatability of positioning of the machine tool. They included:

- dynamic errors related to drive and machine control system,
- kinematic errors related to the elements providing the working units of the machine tool with the movements necessary to perform the operation,
- construction errors related to the stiffness, friction and loads of individual components of the machine.

Statistical analysis

Measurements were made in accordance with the procedures specified in the PN-ISO 230-2: 2014 standard: Machine tool testing rules – part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes. Each measurement cycle was repeated twice and consisted of 11 measurement points. Results obtained for the linear *Y* axis are listed in Table 2 for the following parameters: bidirectional accuracy of positioning *A*, unidirectional accuracy of positioning (forwards $A\uparrow$/backwards $A\downarrow$), bidirectional repeatability of positioning *R*, unidirectional repeatability of positioning (forwards $R\uparrow$/backwards $R\downarrow$), reversal value of an axis $\overline{B}$, and mean reversal value of an axis *B*. The bidirectional accuracy of positioning *A* of the numerically controlled *Y* axis was determined from formula 1:

$$A = max[y_{sri}\uparrow + 2s_i\uparrow; y_{sri}\downarrow + 2s_i\downarrow] - \\ - min[y_{sri}\uparrow - 2s_i\uparrow; y_{sri}\downarrow - 2s_i\downarrow] \quad (1)$$

where: y_{sri} is the bidirectional positioning at a position, s_i is the estimator of the bidirectional standard uncertainty of positioning at a position.

Table 1. Technical specifications of LSP 30 compact laser interferometer

Permissible ambient temperature range	10–35°
Permissible temperature changes during measurement	2°
Laser type	He-Ne
Laser beam diameter	0.8 mm

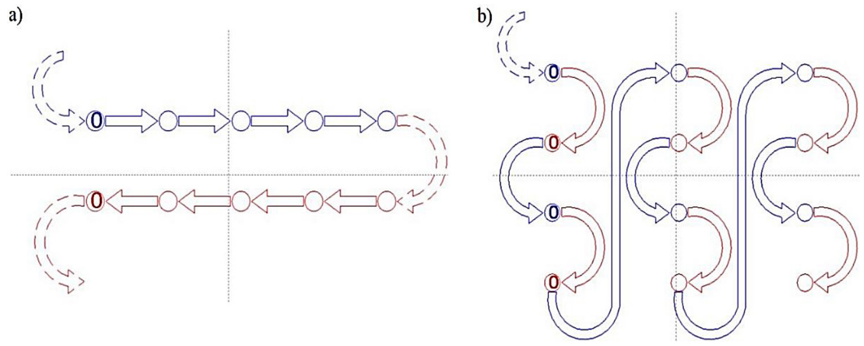

Figure 3. Measurement strategies: a) linear strategy, b) ´pilgrim´ strategy

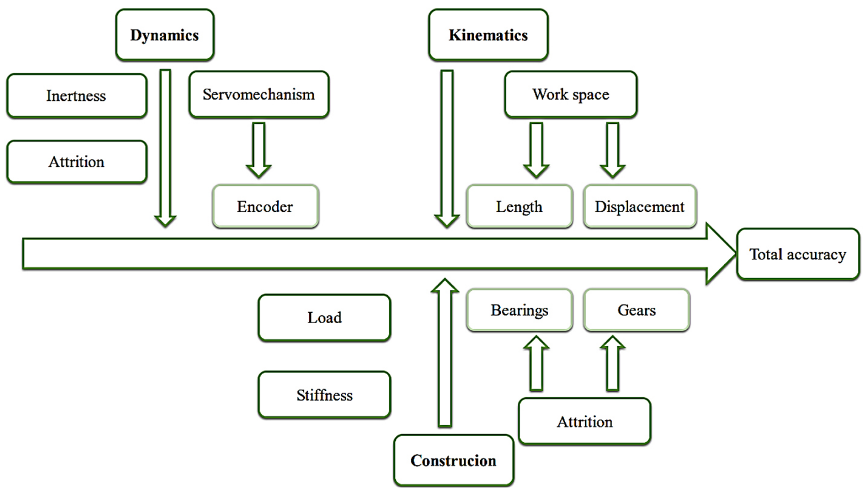

Figure 4. Sources of errors regarding the accuracy and repeatability of positioning of a milling plotter [14]

The values of bidirectional accuracy of positioning of the *Y* axis, forwards $A\uparrow$ and backwards $A\downarrow$, are determined from formulas 2, 3:

$$A\uparrow = max[y_i\uparrow + 2s_i\uparrow] - min[y_i\uparrow + 2s_i\uparrow] \quad (2)$$

$$A\downarrow = max[y_i\downarrow + 2s_i\downarrow] - min[y_i\downarrow + 2s_i\downarrow] \quad (3)$$

where: y_i is the bidirectional systematic positional deviation.

The bidirectional repeatability of positioning *R* was determined from formula (4):

$$R = max[R_i] \quad (4)$$

where: $R = R_i$ is the bidirectional repeatability of positioning at a position determined from formula 5:

$$R_i = max[2s_i\uparrow + 2s_i\downarrow + B_i;\ R_i\uparrow;\ R_i\downarrow] \quad (5)$$

where: B_i is the reversal value at a position ($B_i = y_{sri}\uparrow - y_{sri}\downarrow$), $R_i\uparrow$, $R_i\downarrow$ denote the unidirectional repeatability of positioning at a position.

The reversal value *B* was determined from formula 6:

$$B = max[B_i] \quad (6)$$

Table 2 presents the measurement points in the *Y* axis of the milling plotter, applied in the linear and the ´pilgrim´ strategy.

Table 3 presents lists the parameter values in the *Y* axis of the milling plotter in linear strategy. Table 4 presents lists the parameter values in the *Y* axis of the milling plotter in ´pilgrim´ strategy.

In addition, as part of the statistical analysis, four tests were carried out (Shapiro-Wilk, Anderson-Darling, Lillefors and Jarque-Bera) to check the normality of the values distributions of the obtained plotter accuracy parameters obtained with two strategies. The final stage of the statistical tests was a comparative analysis of their results. The hypothesis of all statistical tests were as follows:

- H_0: the distribution of the data in the sample is a normal distribution,
- H_1: the distribution of the data in the sample is not a normal distribution.

A summary of the normality tests results of the plotter accuracy parameter values distribution obtained with the linear strategy was shown

Table 2. Measurement points in the Y axis of a milling plotter, for the linear and the ´pilgrim´ strategy

Axis	Measurement points										
Y	0	150	300	450	600	750	900	1050	1200	1350	1500

Table 3. Lists of parameter values in the Y axis of a milling plotter in linear strategy

Feed rate v_f [mm/min]	Tolerance					
	Bidirectional accuracy of positioning, A [µm]	Unidirectional accuracy of positioning, A↑A↓ [µm]	Bidirectional repeatability of positioning, R [µm]	Unidirectional repeatability of positioning, R↑R↓ [µm]	Reversal value of an axis, B [µm]	Mean reversal value of an axis, $\overline{B}$ [µm]
1000	554.8	551.2	21.4	11.4	11.9	-7.8
	553.1	550.6	20.8	11.6	11.8	-7.6
	551.2	550.9	21.2	11.3	11.9	-7.8
2000	534.3	525.2	23.8	13.5	13.5	-8.6
	533.9	525.1	23.9	13.3	13.4	-8.6
	534.1	525	23.6	13.6	13.4	-8.7
3000	523.4	513.5	24.6	16.1	13.9	-8.7
	523.4	513.4	24.4	16	13.8	-8.6
	523.6	513.5	24.5	16.2	13.8	-8.6
4000	516.8	505.7	25.4	14.6	12.4	-8.4
	516.7	505.5	25.4	14.5	12.2	-8.4
	516.8	505.8	25.2	14.5	12.2	-8.3
5000	505.4	500	23.9	16.6	13	-8.3
	505.2	499.9	23.8	16.5	12.9	-8.3
	505.3	500.1	23.9	16.7	13.1	-8.1

Table 4. Lists of parameter values in the Y axis of a milling plotter in ´pilgrim´ strategy

Feed rate v_f [mm/min]	Tolerance					
	Bidirectional accuracy of positioning, A [µm]	Unidirectional accuracy of positioning, A↑A↓ [µm]	Bidirectional repeatability of positioning, R [µm]	Unidirectional repeatability of positioning, R↑R↓ [µm]	Reversal value of an axis, B [µm]	Mean reversal value of an axis, $\overline{B}$ [µm]
1000	400.6	391.2	18.1	6.7	12.4	-5.8
	400.4	391.1	18	6.6	12.4	-5.7
	400.4	391	17.8	6.6	12.3	-5.7
2000	395.5	388	15.8	7.7	11.2	-5.2
	395.6	388.2	15.9	7.7	11	-5.3
	395.4	388.1	16	7.8	11	-5.2
3000	393.8	386.9	16.9	9.9	10.7	-4.5
	393.8	386.7	16.7	9.8	10.5	-4.4
	393.7	386.7	16.8	9.8	10.7	-4.5
4000	388.7	383.1	21.5	12.7	10.6	-4.2
	388.8	383.2	21.4	12.5	10.6	-4.2
	388.6	383.1	21.5	12.4	10.4	-4.3
5000	376.5	381.2	21.9	13.4	10.4	-4.3
	376	381.3	21.8	13.5	10.2	-4.2
	376.4	381	21.9	13.5	10.2	-4.4

Table 5. Summary of the normality tests results of the plotter accuracy parameters distribution obtained by the linear strategy

Tolerance [μm]	Shapiro-Wilk	Anderson-Darling	Lillefors	Jarque-Bera
A	0.13	0.191	0.294	0.621
A↑A↓	0.011	0.015	0.057	0.387
R	0.015	0.009	0.005	0.338
R↑R↓	0.071	0.118	0.144	0.543
B	0.12	0.175	0.433	0.502
$\overline{B}$	0.041	0.042	0.072	0.409

Table 6. Summary of the normality tests results of the plotter accuracy parameters distribution obtained by the ´pilgrim´ strategy

Tolerance [μm]	Shapiro-Wilk	Anderson-Darling	Lillefors	Jarque-Bera
A	0.017	0.017	0.037	0.416
A↑A↓	0.1	0.138	0.02	0.577
R	0.006	0.004	0.013	0.381
R↑R↓	0.025	0.036	0.087	0.445
B	0.004	0.02	0.022	0.241
$\overline{B}$	0.007	0.04	0.002	0.384

in Table 5. On the other hand, a summary of the normality tests results of the plotter accuracy parameter values distribution obtained with the ´pilgrim´ strategy was shown in Table 6. Table 7 shows a summary of the statistical analysis results.

Table 5 presents a summary of the normality tests results of the plotter accuracy parameter values distribution obtained with the linear strategy. Values marked in red mean values less than $\alpha = 0.05$. If the p-value is less than 0.05, then the null hypothesis should be rejected. This means that the distribution of the data is not normal. The rejection of the null hypothesis occurred for three-axis plotter accuracy parameters: $A\uparrow A\downarrow$, R and B during the application of the Shapiro-Wilk, Anderson-Darling and Lillefors tests.

Table 6 presents a summary of the normality tests results of the plotter accuracy parameter values distribution obtained with the´pilgrim´ strategy. Values marked in red mean values less than $\alpha = 0.05$. If the p-value is less than 0.05, then the null hypothesis should be rejected. This means that the distribution of the data is not normal. The rejection of the null hypothesis occurred for three plotter accuracy parameters: A, R, $R\uparrow R\downarrow$, B and $\overline{B}$ during the application of the Shapiro-Wilk, Anderson-Darling and Lillefors tests.

Figures 5–7 present histograms showing the frequency of occurrence of the positioning accuracy of the milling plotter values in the statistical sample obtained by the linear strategy. Figures 8–10 present histograms showing the frequency of occurrence of the positioning accuracy of the milling plotter values in the statistical sample obtained by the ´pilgrim´ strategy.

Table 7. The statistical analysis results

Parameter	Obs.	Min	Max	Mean	Std. deviation	α	W	A^2	D	JB	$JB_{critical}$
A	15	505.2	554.8	526.533	16.802	0.05	0.909	0.486	0.169	0.954	5.991
A↑A↓		499.9	551.2	519.027	18.656		0.837	0.916	0.216	1.898	
R		20.8	25.4	23.72	1.465		0.845	1	0.267	2.167	
R↑R↓		11.3	16.7	14.427	1.934		0.892	0.565	0.192	1.223	
B		11.8	13.9	12.88	0.754		0.907	0.501	0.155	1.378	
$\overline{B}$		-8.7	-7.6	-8.32	0.351		0.876	0.739	0.211	1.788	

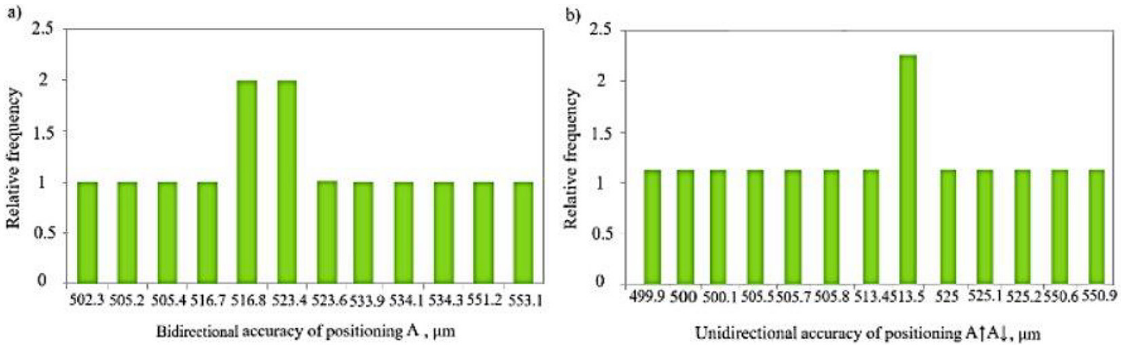

Figure 5. Frequency histograms of the milling plotter accuracy parameters values distribution obtained by the linear strategy: a) bidirectional accuracy of positioning, b) unidirectional accuracy of positioning

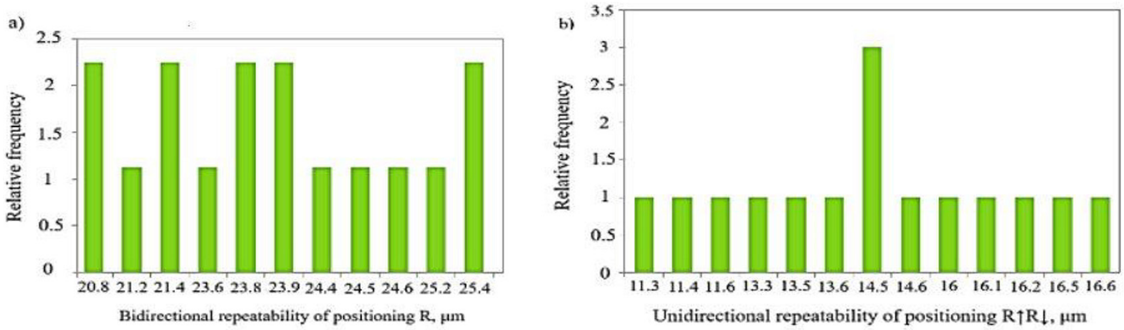

Figure 6. Frequency histograms of the milling plotter accuracy parameters values distribution obtained by the linear strategy: a) bidirectional repeatability of positioning, b) unidirectional repeatability of positioning

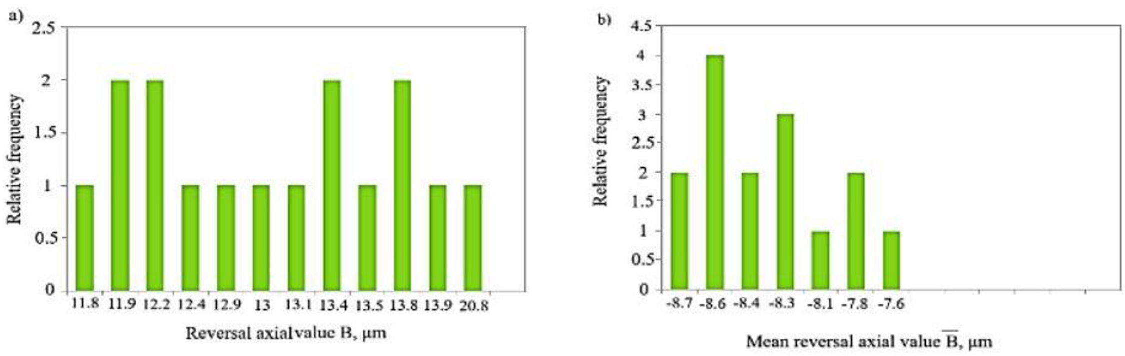

Figure 7. Frequency histograms of the milling plotter accuracy parameters values distribution obtained by the linear strategy: a) reversal axial value, b) mean reversal axial value

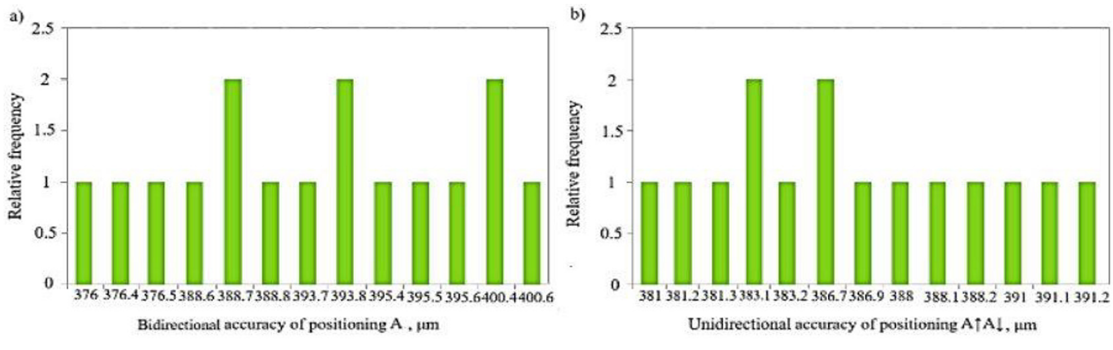

Figure 8. Frequency histograms of the milling plotter accuracy parameters values distribution obtained by the ′pilgrim′ strategy: a) bidirectional accuracy of positioning, b) unidirectional accuracy of positioning

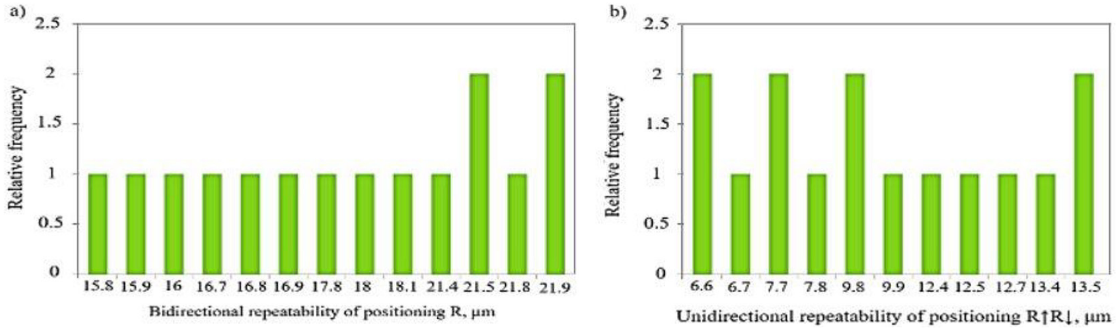

Figure 9. Frequency histograms of the milling plotter accuracy parameters values distribution obtained by the ´pilgrim´ strategy: a) bidirectional repeatability of positioning, b) unidirectional repeatability of positioning

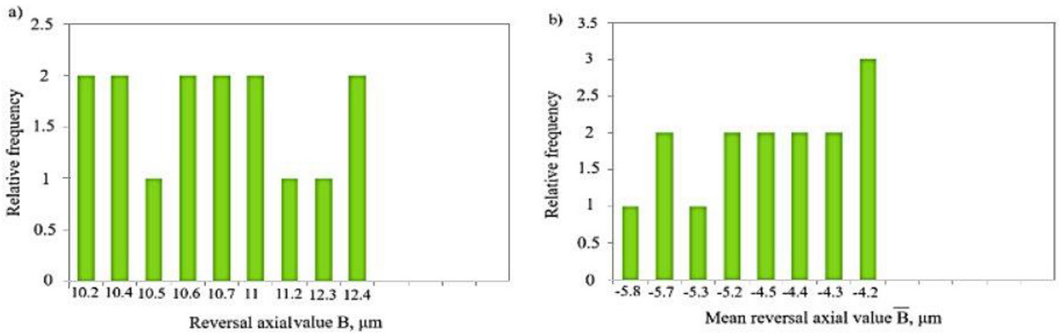

Figure 10. Frequency histograms of the milling plotter accuracy parameters values distribution obtained by the ´pilgrim´ strategy: a) reversal axial value, b) mean reversal axial value

Verification of the values distribution normality for each positioning accuracy parameter of the milling plotter showed that for the linear strategy the results distributions of the A, $R{\uparrow}R{\downarrow}$ and B parameters most closely resemble the normal distribution, which means that a significant part of the observations were centred around the mean. However, the results distribution of the $A{\uparrow}A{\downarrow}$, R and $\overline{B}$ parameters showed asymmetry. The values distribution for the R parametr is right-sided asymmetry. The values distribution for the $A{\uparrow}A{\downarrow}$ parameter is left-sided asymmetry.

For the ´pilgrim´ strategy, the scores distribution for the $A{\uparrow}A{\downarrow}$ most closely resemble the normal distribution, which means that a significant part of the observations were centred around the mean. The result distribution of the A, R, $R{\uparrow}R{\downarrow}$, B and $\overline{B}$ parameters showed asymmetry. The values distribution for the A, $R{\uparrow}R{\downarrow}$ and B is right-sided asymmetry. The values distribution for the R and $\overline{B}$ parameters is left-sided asymmetry.

Verification of the value distribution normality for each parameter confirmed the results agreement of the four distribution normality tests.

Due to the nature of the input data in form of the feed rate parameter and the output data in form of positioning and repeatability accuracy parameters, a predictive model was selected that best fits the optimal single value of the input quantity. In order to check relationship between the v_f parameter and the A, $A{\uparrow}A{\downarrow}$, R, $R{\uparrow}R{\downarrow}$, B and $\overline{B}$ parameters, a test was performed. The Pearson's correlation coefficient was used in the test. The results of checking linear correlation between the feed rate parameter and the plotter accuracy parameters are shown in Figure 11.

In the linear strategy the matrix is symmetric. Each pair has a correlation coefficient ranging from -1 to 1. There is a significant negative correlation between the feed rate parameter and the A, $A{\uparrow}A{\downarrow}$ and B milling plotter accuracy parameters. The R and $R{\uparrow}R{\downarrow}$ parameters show a positive correlation with the feed rate parameter. This means that R and $R{\uparrow}R{\downarrow}$ parameter values are correlated with the value preceding it. A positive correlation means that one value could be predicted from another based on the data. A complete linear correlation between the A and $A{\uparrow}A{\downarrow}$ parameters is also noticeable. The relationship between feed rate parameter and the plotter positioning accuracy and repeatability parameters varies for different parameters. While the v_f parameter increase, the

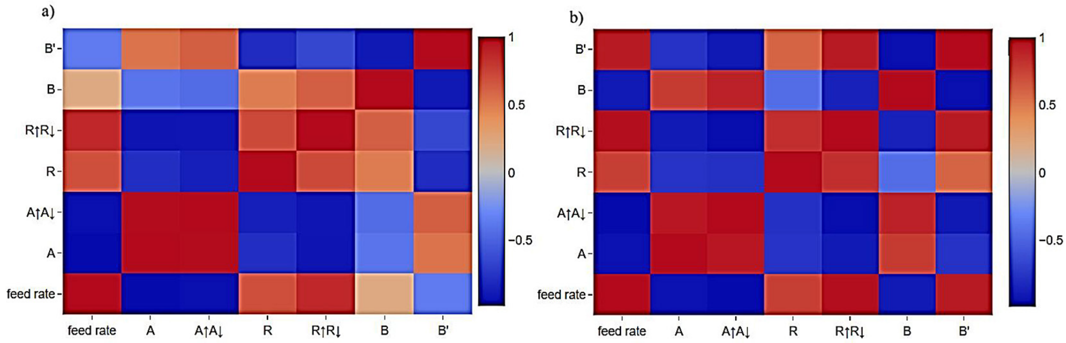

Figure 11. Correlation matrix in strategies: a) linear, b) ´pilgrim´

values of the A, $A↑A↓$ parameters decrease and the R, $R↑R↓$, B and $\overline{B}$ parameters increase.

When it comes to the ´pilgrim´ strategy the matrix is symmetric. There is also a significant negative correlation between the feed rate parameter and the A, $A↑A↓$ and B milling plotter accuracy parameters. The R, $R↑R↓$ and $\overline{B}$ parameters show a positive correlation with the feed rate parameter. This means that R, $R↑R↓$ and $\overline{B}$ parameters values are correlated with the value preceding it. A positive correlation means that one value could be predicted from another based on the data. A complete linear correlation between the A and $A↑A↓$ parameters is also noticeable. The relationship between feed rate parameter and the plotter positioning accuracy and repeatability parameters varies for different parameters. While the v_f parameter increase, the values of the A, $A↑A↓$ and B parameters decrease and the R, $R↑R↓$ and B parameters increase. This may have an impact in production applications where the feed rate needs to be controlled or predicted based on the accuracy and repeatability results of a milling plotters positioning.

Figures 12–14 shows the results of the accuracy parameters dependence of the milling plotter as a function of the feed rate. Figure 12 shows the changes in the unidirectional and bidirectional

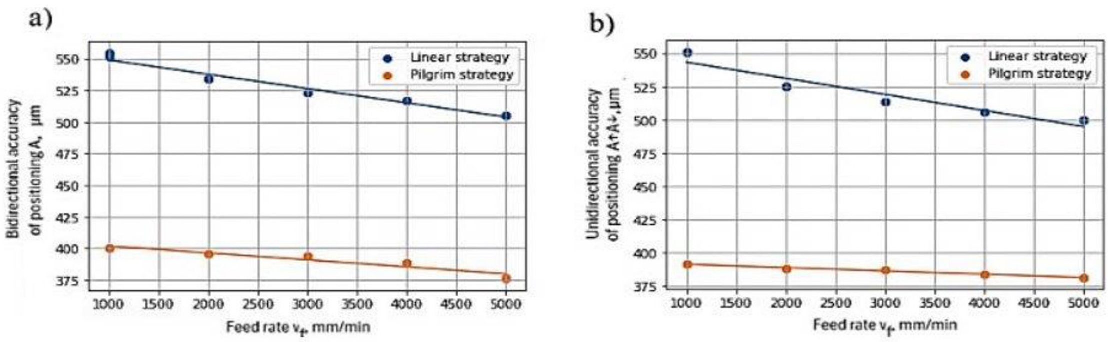

Figure 12. Positioning accuracy of the milling plotter: a) bidirectional accuracy, b) unidirectional accuracy

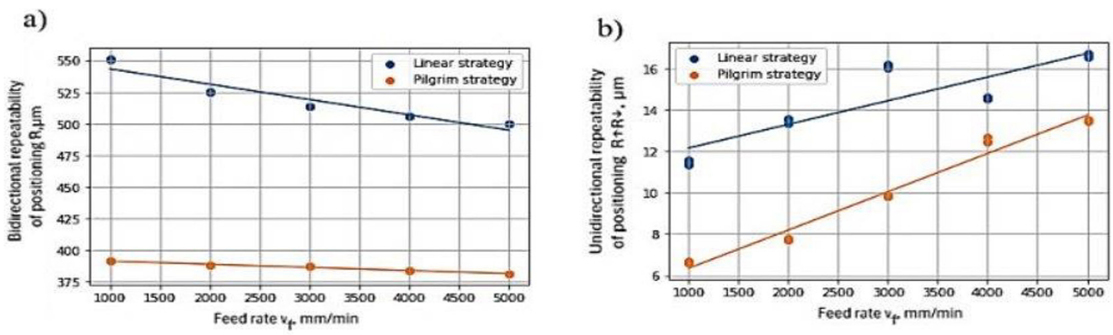

Figure 13. Positioning repeatability of the milling plotter: a) bidirectional repeatability, b) unidirectional repeatability

positioning accuracy of the milling plotter as a function of feed rate obtained by linear and ´pilgrim´ strategies. Figure 13 shows the changes in the unidirectional and bidirectional positioning repeatability of the milling plotter as a function of feed rate obtained by linear and ´pilgrim´ strategies. Figure 14 shows the changes in the reversal and its mean value of the *Y* axis of the milling plotter as a function of feed rate obtained by linear and ´pilgrim´ strategies.

Figure 12 shows that as the feed rate v_f increases, the bidirectional and unidirectional positioning accuracy of the milling plotter decrease in both measurement strategies. Figure 13 shows that as the feed rate v_f increases, the unidirectional positioning repeatability of the milling plotter decreases. In addition, as the feed rate v_f increases, the bidirectional positioning repeatability of the milling plotter increases. Figure 14 shows that as the feed rate v_f increases, the axial return value obtained by the linear strategy increases. In the ´pilgrim´ strategy, the axial return value parameter decrease as the feed rate v_f increases. The average axial return value obtained by the linear strategy decreases with the increase of the feed rate v_f. In the pilgrim strategy the average axial return value increase.

The measurement carried out in accordance with the linear strategy was based on a single raid of the plotter's measuring head to a specific measurement point. Whereas, in the ´pilgrim´ strategy, the plotter head moved to one measurement point 4 times.

Numerical modeling of the milling plotter accuracy parameters using Machine Learning Models

Based on the obtained experimental studies, numerical modeling of the milling plotter positioning and repeatability parameters was carried out using machine learning. Due to the characteristics of the data, one regression method was chosen – linear regression. To choose a candidate for parameter optimization, the above-mentioned method was tested. The following metrics were used for comparison: R^2 (coefficient of determination), the mean squared error (MSE), root mean square error (RMSE), The mean absolute

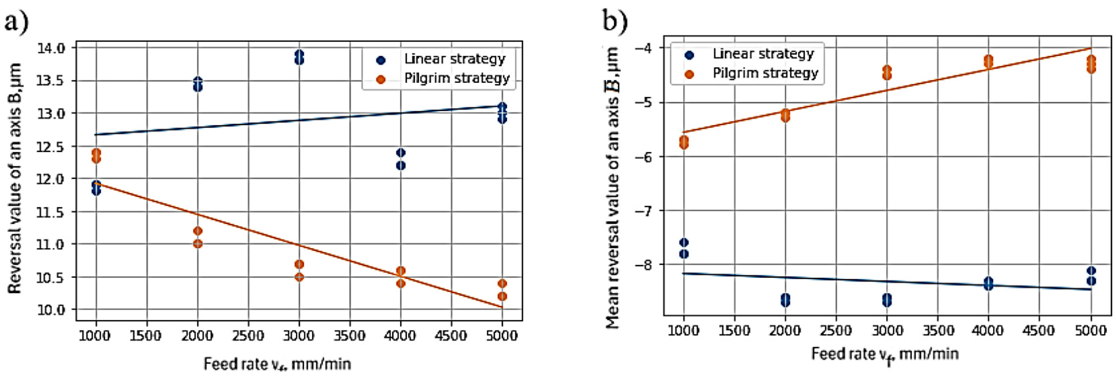

Figure 14. Reversal value of the milling plotter axis: a) reversal value, b) mean reversal value

Table 8. Summary of linear regression metrics for the tested accuracy parameters of the milling plotter

Metrics	Parameter [µm]					
	A	A↑A↓	R	R↑R↓	B	$\overline{B}$
R^2	0.959	0.904	0.485	0.753	0.046	0.13
MSE	19.034	22.462	1.537	1.449	0.83	0.142
RMSE	4.363	7.243	1.239	1.2034	0.911	0.378
MAPE	0.587	0.989	3.962	5.196	5.047	3.177
Cp	2					
AIC	16.177	21.246	3.596	3.3	0.516	8.29
SBC	15.395	20.465	2.815	2.519	-0.265	9.071
PC	0.095	0.223	1.199	0.577	2.225	2.03

percentage error (MAPE), Cp, AIC, SBC and PC. A summary of the metrics is shown in Table 8.

Table 8 shows that the linear regression model achieved the best R2 score of 0.959 for the *A* parameter, an MSE of 0.83 for the *B* parameter, an RMSE of 0.378 for the parameter $\overline{B}$, an MAPE of 0.587 for the *A* parameter. The *Cp* metric is a good fit for the studied model. In addition, the best AIC score of 8.29 and SBC of 9.071 was recorded for the $\overline{B}$ parameter and the highest accuracy of the PC metric of 0.095 was recorded for the *A* parameter. On the basic of the linear regression results, regression equations were determined for all tested parameters. The changes in A parameter for the feed rate v_f= 5000 mm/min and the linear strategy were determined from the formula 7:

$$A = 0.56183 - (k_1 \cdot v_f) \tag{7}$$

$$A = 0.56183 - (0.00146 \text{ min} \cdot 5000 \text{ mm/min}) = = 554.8 \text{ µm} \tag{8}$$

Changes in the remaining parameters were determined in the same way. The relationship between the positioning accuracy and repeatability parameters of the milling plotter and strategy is complex and varies for different parameter. Given laboratory practice, it may be most useful to determine all the factors that affect the measurement accuracy. It should be emphasized that the more accurate the factors analysis influencing the milling plotter positioning accuracy measurement, the more accurately the machine error is determined and the more effectively errors in the execution of shape contours can be minimized. This could have implications in industrial applications where the shape contour accuracy needs to be controlled or predicted based on the measurement conditions, strategy and the accuracy and repeatability of numerical machines.

CONCLUSIONS

Experimental studies focused on the evaluation of the impact of measurement conditions and measurement strategies on the positioning accuracy and repeatability of the three-axis milling plotter. The results of this study have led to the following conclusions:

- the test stand was exposed to sunlight during the tests. The recorded air temperature was 24 °C and the air humidity was 45%. Environmental factors slightly affected to the plotter positioning accuracy. Significant changes in air temperature and humidity may lead to differences in the plotter tested accuracy parameters values,
- the laser interferometer, the measurement strategies, position calibration were additional factors affecting the values of the tested accuracy parameters,
- the linear measurement strategy proved to be less accurate but more efficient. Whereas, the ´pilgrim´ measurement strategy turned out to be more accurate strategy. In the linear strategy, measuring head only hovers over the measuring point once during a single measurement. In the ´pilgrim´ strategy, measuring head only hovers over the measuring point four times. The measurement repeatability at the single point increases the measurement accuracy and reduces the possibility of measurement error occurrence.

The linear regression model achieved the best R^2 score of 0.959 for the *A* parameter, an MSE of 0.83 for the *B* parameter, an RMSE of 0.378 for the parameter $\overline{B}$, an MAPE of 0.587 for the A parameter. The *Cp* metric is a good fit for the studied model. In addition, the best AIC score of 8.29 and SBC of 9.071 was recorded for the $\overline{B}$ parameter and the highest accuracy of the PC metric of 0.095 was recorded for the *A* parameter.

The conducted research provides valuable cognitive conclusions allowing for the assessment of cause-and-effect relationships between the measurement conditions and measurement strategies and the positioning accuracy and repeatability parameters of the milling plotter. This information is needed for optimizing process and can significantly contribute to improving the efficiency machining process, the accuracy of shaped contours and the numerical machines accuracy. By understanding how measurement conditions and measurement strategies affect positioning accuracy, manufacturers can make informed decisions to enhance the overall efficiency and productivity of the machining process.

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