EFFECTS OF PART COORDINATE SYSTEM APPOINTMENT ON CMM MEASUREMENT

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Abstract. Accurate measurement of the components before assembly, as well as the spare parts for agricultural machines, is a crucial issue for the correct and failureless machinery work. In the paper, measurement with Coordinate Measuring Machines (CMMs) is discussed from the perspective of accuracy affected by the part coordinate system appointment. In general, the CMM procedure consists of determining the spatial coordinates of measurement points on the surface of a measured object, and then via certain calculations, the best-fitting geometrical elements are ascribed to the probing points either in the CMM coordinate system or in the coordinates of the measured object. From these elements, dimensions of the measured part are derived with certain accuracy. In the experiments, a contact measurement was completed with a stylus equipped with a ball tip maintaining the same distance between its centre and the measured surface in all directions. There are many sources of uncertainty in CMM measurement, but the errors introduced during determination of the Part Coordinate System (PCS) affect all the subsequent measurement results obtained from respective chains of calculations. Thus, the study is devoted to the uncertainty reduction through the analysis of PCS appointment accuracy. Experimental measurements were performed using CMM Mitutoyo Crysta-Apex C7106 and the standard gage blocks. Theoretically, accurate identification of the probing points should provide accurate determination of the PCS coordinates X, Y, and Z. However, when measuring such an accurate object as a gage block, the results appeared to be dependent on the measurement method. In the experiments, four methods were tested. Dependent on the measurement strategy, PCS appointment method and particular settings of the measurement parameters, the Part Coordinate System generated different errors from negligibly small ones up to 10 μm.

Keywords: coordinate measurement system, CMM, CNC measurement, measurement strategy.

Introduction

Dimensional accuracy of the components is an important issue of quality when producing complex devices and machines [1; 2]. Coordinate measurements have gained a position of the basic technique used and quality inspection and control in the machine industry [3], due to the possibility of measurement both dimensions and form deviations, as well as position errors of components with complex geometry [4]. The measurement principle with Coordinate Measuring Machines (CMMs) involves determination of the spatial coordinates of the points on the surface of an object and subsequent calculations in order to assign the best-fitting geometrical elements [5].

Due to the complex procedures, there are many sources of uncertainty in CMM measurement [6; 7], but the errors introduced during determination of the local coordinate system, also referred to as the Part Coordinate System (PCS), affect all the subsequent measurement results obtained from respective chains of calculations [8]. Moreover, a spherical tip at the end of the typical stylus used in the CMM's measuring heads not necessarily maintains a uniform shape, which may generate further errors dependent on the movement directions [9]. Usually, it is recommended to determine probing points in directions of the probe ball tip consistent with its shaft axis. However, its movement should also be perpendicular to the measured surface in the contact point [10], which is not always possible due to the complexity of the measured part. Thus, additional errors may be generated due to the lack of calibration at different angles of the stylus.

This paper presents a study concerning the errors that may appear as a result of an inappropriate measurement strategy and appointment of the part coordinate system.

Materials and methods

As a reference dimension, the gage block of nominal length $W = 20$ mm was chosen from the set MLAa, 3rd class, produced by FWP company (Warsaw, Poland). Its accuracy of dimension reproduction in the middle area can be described as $w = 0.2 \pm 0.004 \cdot L$ μm, where measured $L = W = 20$ mm gives the accuracy of 0.3 μm. During the experiments, the gage block was placed vertically, with the reference dimension along x-axis of the Coordinate Measurement Machine (CMM). The gage block was fixed on a polished steel base with a spring clamp, as it is shown in Figure 1. This way of fixation allowed for safe and stable accomplishment of all measurements with the same, unchanged position of the gage block, including the measurement involving the maximum probe rotation angle.

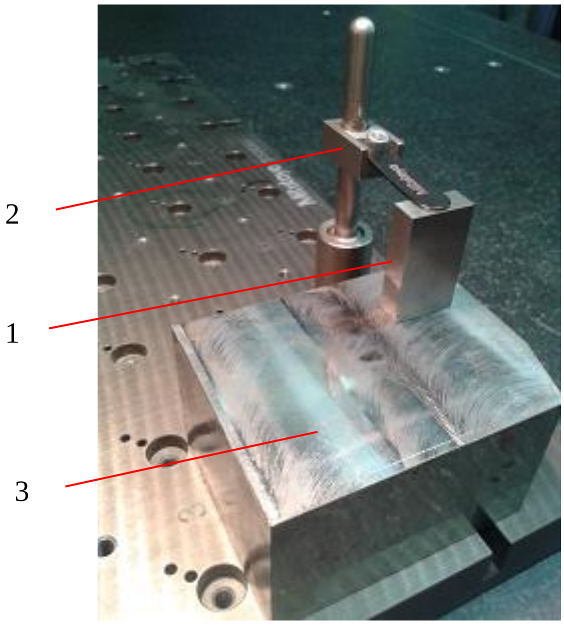

Fig. 1. **Fixation of the gage block:** 1 – gage block, 2 – spring clamp, 3 – steel base

All the experiments were carried out using the Mitutoyo Crysta-Apex C7106 CMM with software MCOSMOS-v3.2 R13, equipped with a Renishaw measuring head type RH-10Q. Permissible errors of this CMM were defined as follows.

- Length error is calculated as $MPE_{E\,=}\,1.7 \pm L \cdot 10^{-2}$ μm, which for the reference length $L = 20$ mm reaches 2 μm.
- Probing head error $MPE_{P\,=}\,1.7$ μm.
- Scanning head error $MPE_{THP\,=}\,2.3$ μm.
- Permissible test time $MPT_{T\,=}\,110$ s.

The scanning probe was applied, type SP25M with the ball tip of diameter d = 2 mm. The screen with complete configuration of the probe tree, including the stylus adaptor, is shown in Figure 2, while the rotational angles A and B are shown in Figure 3.

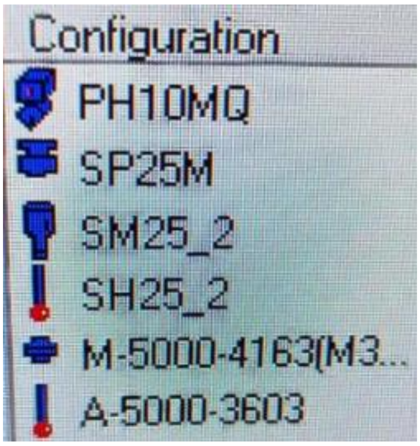

Fig. 2. **Measurement tree of the stylus used in experiments**

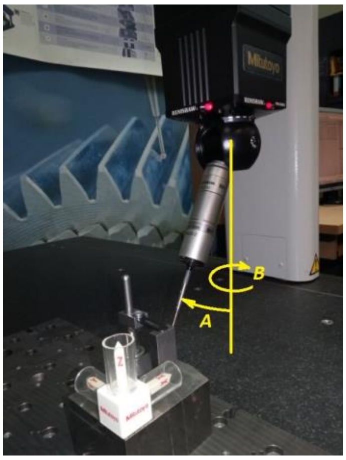

Fig. 3. **Rotation angles of the stylus**

In the research, two strategies of PCS appointment were used combined with four measurement methods that were compared with the interferometric or nominal length W of the gage block.

The strategies were defined as follows:

1. In the first strategy, from the left, front, and upper surfaces of the gage block shown in Figure 1, the probing points were collected in CNC mode, 4 points from each one. Here, the probe rotation angles depicted in Figure 3 were A = 0º, B = 0º. Considering the constructional limitations of the stylus, the points were placed on higher part of the gage block, ca. 10 mm down from the upper surface. These points were joined together to define respective planes that determined the local coordination system with its centre in the common point of the three planes. The main plane was defined corresponding with the upper plane of the gage block, while the x-axis of PCS was defined as the intersection line between the upper surface and the front surface.
2. In the second strategy, the left, front, and upper surfaces of the block gage were measured in CNC mode with the point distributed similarly as in strategy 1. However, the main plane was defined corresponding with the left surface of the gage block, while the x-axis of the local coordinate system was perpendicular to the main plane.

The experiments were all performed in CNC mode after the stylus was calibrated at different combinations of rotation angles B = –90º and subsequent A = 0º, 15º, 30º, 45º, 60º, 75º, and 90º. Each measurement in CNC mode started from the point (24, 5, –5) and the probe moved along the x-axis of the local coordinate system. Using four different methods, 50 repetitions were made to measure the reference dimension of the gage block.

The methods of measurement illustrated in Figure 4 were:

- In method 1, coordinate x of the probing point M placed on the gage block right surface was determined, so that the measured value was considered $N = M_x$;
- Method 2 consisted of distance measurement between the point M and the left face surface of the gage block along the axis x, so that the measured value was considered $N = a_x$;
- Method 3 involved determination of the coordinate x of the probe ball tip centre O minus the ball radius, when the stylus was triggered after touching the right face surface. Thus, the measured value was considered $N = O_x - 0.5d$. During calibration it was found that the probe ball tip diameter was between 2.000 and 2.002 mm dependent on the stylus rotation angle;
- In method 4, the distance was measured along the x-axis between the ball tip centre position O, and the left surface, minus the ball diameter. Thus, it was measured $N = O_x - 0.5d$.

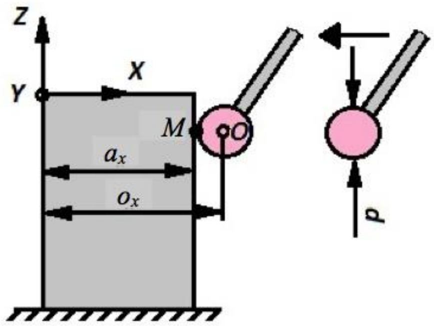

Fig. 4. **Illustrations of the measurement methods**

In methods 2 and 4, the compensated measuring points were applied, where the compensation of the probe radius is performed along the direction of the points collection during the measurement. In turn, non-compensated points were applied in methods 1 and 3. Based on the probe ball tip centre coordinates, the subsequent length measurement is performed with automatic compensation of the ball radius.

Thus, with 7 stylus rotation angles, 2 PCS appointment strategies, 4 measurement methods and 50 repetitions, the total number of experimental measurements was 2800.

Results

In the investigations, for all tested strategies and methods specified above, the common reference value was chosen denoted Δ. It represented the difference between the average value N of the measurement results of the interferometric length W, and its nominal value W = 20 mm. For each set of 50 repetitions, the standard deviation S_n was calculated, which appeared to be from 0.1 up to 0.3 µm.

Since the Shapiro-Wilk statistical test provided the ground to assume that the data is not normally distributed, parameters of Student's *t*-distribution were applied. The range of the measured values was determined as $\pm 0.461 \cdot S_n$ for probability 99.5% with 49 degrees of freedom and the parameter $t = 3.262$.

Uncertainty of the value Δ was calculated according to the typical procedure for a combined standard uncertainty recommended by GUM [11]. It involved uncertainty of the gage block and significantly smaller uncertainty of the measurement and was found to not exceed 0.35 µm. The average values of the measured distance *N* with the corresponding differences Δ are presented in Tables 1 and 2, separately for each strategy applied.

Table 1

Average values of the measured distance *N* and corresponding differences Δ obtained for strategy 1

Stylus rotation angle	Method 1		Method 2		Method 3		Method 4	
***A*, °**	***N*, mm**	**Δ, µm**	***N*, mm**	**Δ, µm**	***N*, mm**	**Δ, µm**	***N*, mm**	**Δ, µm**
0	19.998	1.98	19.992	7.56	19.998	1.6	19.992	8.00
15	20.000	0.00	19.994	5.70	19.999	0.62	19.994	6.00
30	20.000	0.00	19.994	5.70	19.999	0.08	19.994	6.00
45	20.000	-0.08	19.994	5.59	20.000	0.02	19.994	5.92
60	20.0002	-0.16	19.994	5.70	20.000	0.02	19.994	5.92
75	20.001	-0.84	19.995	4.94	20.001	-0.98	19.995	5.12
90	20.000	0.04	19.994	6.04	20.000	-0.22	19.994	6.20

Table 2

Average values of the measured distance *N* and corresponding differences Δ obtained for strategy 2

Stylus rotation angle	Method 1		Method 2		Method 3		Method 4	
***A*, °**	***N*, mm**	**Δ, µm**	***N*, mm**	**Δ, µm**	***N*, mm**	**Δ, µm**	***N*, mm**	**Δ, µm**
0	19.999	0.79	19.994	6.05	19.999	0.88	19.994	6.40
15	20,000	0.44	19.995	5.17	19.999	0.66	19.994	5.60
30	20,000	0.45	19.995	5.23	20.000	0.46	19.994	5.60
45	19.999	0.60	19.995	5.38	19.999	0.58	19.994	5.66
60	19.999	0.60	19.995	5.50	19.999	0.65	19.994	5.73
75	20,000	0.36	19.995	5.02	20.000	0.29	19.995	5.18
90	20.000	0.31	19.996	4.71	20.000	0.07	19.994	5.60

Figures 5 and 6 present diagrams of $\Delta = f(A)$ functions for the two respective strategies of PCS appointment.

Discussion

From the data presented above, it can be seen that the largest differences Δ between the interferometric length *W* of the gage block and the measurement result *N* took place after strategy 1 was used for PCS appointment, and methods 2 and 4 applied for measurement. Notably, these covered also the largest dispersion of Δ values, which was up to 3 µm. Undoubtedly, this result was closely connected with the position of the *x*-axis of the local coordinate system (PCS). The successful compensation could be achieved if the *x*-axis was perpendicular to the left surface of the gauge block. Perhaps, it can be concluded that the probe did not move accurately along this axis during the measurement. In fact, the gage block used in the experiments reproduced the length of 20 mm as a distance between the central point of one surface and the other surface, but it did not necessarily reproduce accurate perpendicular positioning of the upper, left, and right surfaces. Meanwhile, proper definition of the *x*-axis depended mostly on the determination accuracy of the constituting planes on those surfaces. When measuring the front surface and the left one with the same stylus as in case of the upper surface, deviation from the right angle was observed, which reached up to several angle seconds.

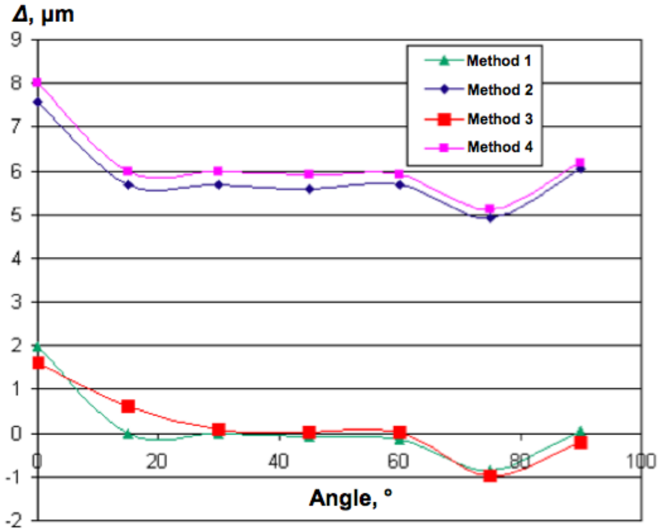

Fig. 5. **Differences Δ between average measured values *N* and gage block nominal *W* for different methods applied for strategy 1**

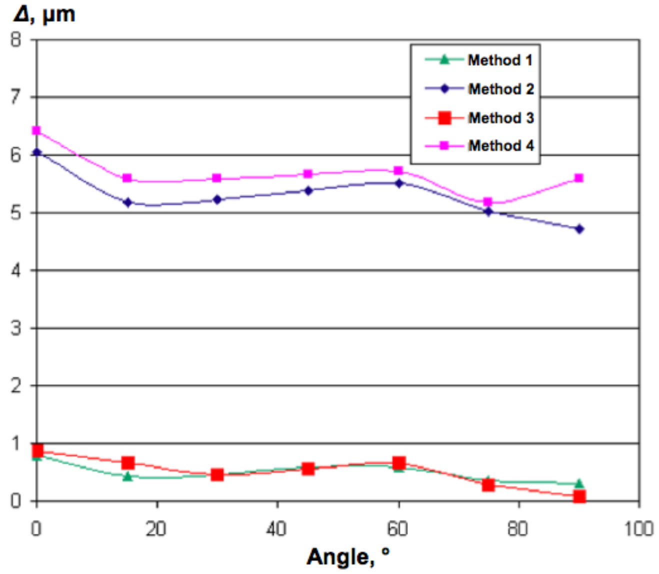

Fig. 6. **Differences Δ between average measured values *N* and gage block nominal *W* for different methods applied for strategy 2**

On the other hand, the smallest differences Δ were obtained after strategy 2 was used in combination with methods 1 and 3 of non-compensated point measurement. These combinations provided also the smallest dispersion of Δ values below 1 μm.

From the analysis of diagrams representing results from methods 2 and 4 in Figures 5 and 6, the higher accuracy of the strategy 2 can be derived. It provided reduction of differences Δ by ca. 1 μm, compared to those obtained after strategy 1 was used. This effect is especially significant in combination with the measurement of non-compensated point.

Notably, the experiments dealt with the simplest linear distance measurement, which was able to generate the length error MPE_E 5 times larger than the nominal value for this CMM. Obviously, when measuring more complex parts, the uncertainty propagation can significantly increase the final effect of the improper combination of the PCS appointment strategy and the measurement method.

Considering individual characteristics of the tested CMM, it appeared quite possible that in other conditions such an error would be smaller or even negligible. However, it seems worthy to pay attention to the specified problems and to repeat the experiments using other CMMs and software.

Conclusions

1. Coordinate measurement of a non-compensated point is a universal one and should be considered as a basic method for CNC measurement mode with CMM.
2. Compensated point measurement should be rather optional in coordinate measurement technique, and it requires accurate determination of the probe movement direction related to the measured surface.
3. Since both the strategy of PCS appointment and the method of the dimensional measurement with CMM may significantly reduce the final accuracy, their combinations should be thoroughly analysed and properly adopted to the individual measurement tasks.

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References

[1] Wu C., Chen C., Li C., Wang L., Geng Y., Zhang T. Analysis of machined surface quality for multi-feature standard parts. Journal of Manufacturing Processes, vol. 115, 2024, pp. 452-465. DOI: 10.1016/j.jmapro.2024.02.037

[2] Gevorkyan E., Mamalis A., Vovk R., Semiatkowski Z., Morozow D., Nerubatskyi V., Morozova O. Special features of manufacturing cutting inserts from nanocomposite material Al_2O_3-SiC. Journal of Instrumentation, 16, 2021, P10015. DOI: 10.1088/1748-0221/16/10/P10015

[3] Wojtyła M., Rosner P., Płowucha W., Forbes A.B., Savio E., Balsamo A. Validation of the sensitivity analysis method of coordinate measurement uncertainty evaluation. Measurement, vol. 199, 2022, art. 111454. DOI: 10.1016/j.measurement.2022.111454

[4] Mazur T, Rucki M., Gutsalenko Y. Accuracy analysis of the curved profile measurement with CMM: a case study. Facta Universitatis, Series: Mechanical Engineering, vol. 21, iss. 1, 2023, pp. 121-135. DOI: 10.22190/FUME210507063M

[5] Savio E. Coordinate Measuring Machine. In Chatti S., Laperrière L., Reinhart G., Tolio T. (Eds.), CIRP Encyclopedia of Production Engineering. Berlin/Heidelberg: Springer, 2019.

[6] Sładek J.A. Coordinate Metrology: Accuracy of Systems and Measurements. Berlin/Heidelberg: Springer, 2016. DOI: 10.1007/978-3-662-48465-4_4

[7] Štrbac B., Ačko B., Havrlišan S., Matin I., Savković B., Hadžistević M. Investigation of the effect of temperature and other significant factors on systematic error and measurement uncertainty in CMM measurements by applying design of experiments. Measurement, vol. 158, 2020, art. 107692. DOI: 10.1016/j.measurement.2020.107692

[8] Senin N., Catalucci S., Moretti M., Leach R.K. Statistical point cloud model to investigate measurement uncertainty in coordinate metrology. Precision Engineering, vol. 70, 2021, pp. 44-62. DOI: 10.1016/j.precisioneng.2021.01.008

[9] Ito S., Tsutsumi D., Kamiya K., Matsumoto K., Kawasegi N. Measurement of form error of a probe tip ball for coordinate measuring machine (CMM) using a rotating reference sphere. Precision Engineering, vol. 61, 2020, pp. 41-47. DOI: 10.1016/j.precisioneng.2019.09.017

[10] Mazur T., Cepova L., Szymanski T., Rucki M. Analysis of the Planar Point Identification Accuracy in CMM Measurements. Sensors, vol. 22, nr 18, 2022, art. 7005. DOI: 10.3390/s22187005

[11] JCGM 100:2008. Evaluation of measurement data. Guide to the expression of uncertainty in measurement.