

Comparison of the Accuracy of Measurements of the Geometry of Parts Using Coordinate Measuring Machines in Manual and Programmed Operating Modes

Nefelov I.S., Filatov V.V., Taldykin D.S.*

State University of Management, Moscow, Russia

*corresponding author

Abstract. This study compares the accuracy and repeatability of dimensional measurements performed on a coordinate measuring machine in manual and programmed operating modes. A Cummins diesel-engine piston was used as the test object; its diameter was measured in a production-specified section located 119 mm from the piston-skirt end. The experiment comprised part fixturing, establishment of the workpiece coordinate system by the 3-2-1 method, and repeated measurements in both modes. A Mezorix Atlas C 686 Basic CMM equipped with a Renishaw TP20 probe was used. In manual mode, the self-learning function recorded contact-point coordinates and approach vectors. In programmed mode, the RationalDMIS routine refined approach vectors according to nominal geometry and maintained a controlled contact speed. Ten repeated measurements were completed in each mode, and manual-mode reproducibility was additionally evaluated by three operators. The programmed mode produced a mean diameter of 157.7548 mm, a standard deviation of 0.0012 mm, and an uncertainty of ± 0.0024 mm. The corresponding manual-mode values were 157.7382 mm, 0.0057 mm, and ± 0.0114 mm. Relative to manual control, programmed control reduced the absolute deviation from the nominal diameter by 39.1% and the standard deviation by a factor of 4.75. The results show that automated control improves measurement repeatability by stabilizing probe direction and speed, whereas manual measurement remains dependent on operator skill. Self-learning is recommended for rapid generation of an initial inspection program followed by software-based optimization.

Keywords: coordinate measuring machines, measurement accuracy, programmed control, manual control, probe approach vector, self-learning mode.

Introduction

When performing coordinate measurements, coordinate systems are required. A distinction is made between a machine coordinate system and a workpiece coordinate system. The Machine Coordinate System is fixed relative to the physical coordinate axes of the coordinate measuring machine. It is determined at the design and manufacturing stage of the coordinate measuring machine and is usually located in one of the corners of the machine. The Workpiece Coordinate System is a coordinate system that is fixed relative to the workpiece (Fig. 1). This coordinate system depends on the position of the workpiece and is determined based on its design.

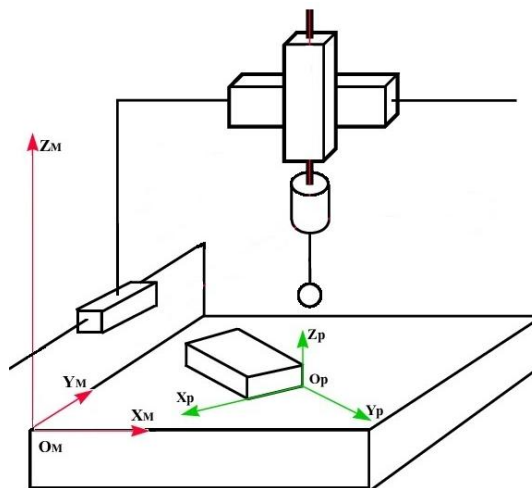


Fig. 1. - Coordinate systems for measurements on a coordinate measuring machine: O_M - origin of the machine coordinate system; X_M , Y_M , Z_M - axes of the machine coordinate system; O_P - origin of the workpiece coordinate system; X_P , Y_P , Z_P - axes of the workpiece coordinate system. Source: compiled by the authors.

The configuration of the measured parts is very diverse, but almost any part consists of at least several surfaces (with the exception of the simplest geometric bodies such as a sphere). It is known that surfaces consist of many points. To determine the position of these points, coordinates along the X, Y, Z axes are used. However, even knowing

the coordinates of all points on the surface, it is difficult to perform correct measurements of this surface on a coordinate measuring machine, since the orientation of the surface in space is unknown. To specify the orientation of the surface in space, normal unit vectors are used, which determine the direction perpendicular to the tangent plane at a given point on the surface (Fig. 2) [1].

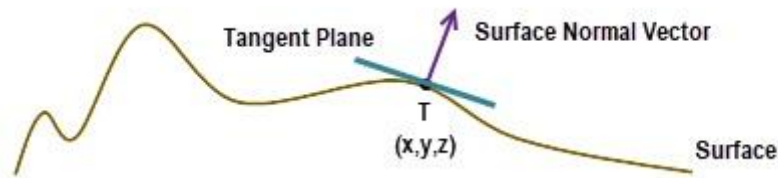


Fig. 2. - Tangent plane to the surface and the unit normal vector. Source: compiled by the authors.

The direction of the unit normal vector $\vec{n}$ to a point on the surface is determined by specifying its components $I(1,0,0)$, $J(0,1,0)$, $K(0,0,1)$, representing the projections of this vector onto the coordinate axes X , Y , Z , respectively. Then the direction of the normal unit vector can be written as follows:

$$\vec{n} = (I, J, K) \quad (1)$$

Normal vectors of surfaces play a huge role in coordinate measurements, as they allow determining the optimal direction of approach of the measuring tip to a surface point during contact measurement (Fig. 3).

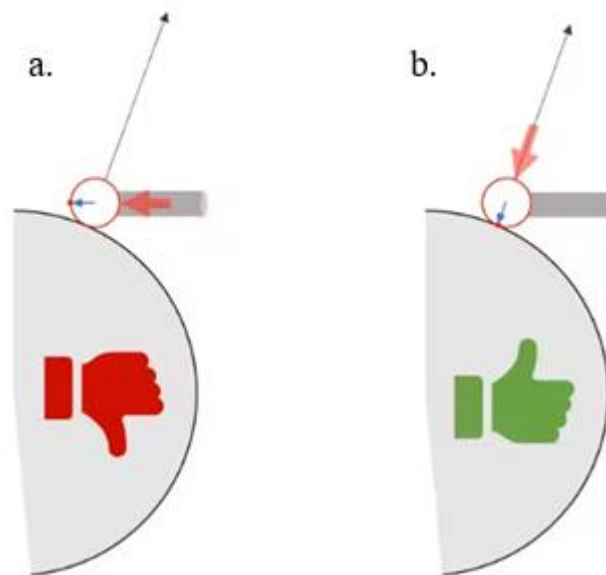


Fig. 3. - Non-optimal (a) and optimal (b) directions of measuring-tip motion at surface contact. Source: [2].

"Sliding" touches significantly reduce the accuracy and repeatability of measurements. Therefore, their use is undesirable when performing high-precision measurements. When performing measurements, it is recommended that the direction of the motion vector of the measuring tip should be in a cone of $\pm 20^\circ$ relative to the normal vector to the surface point. It is considered ideal when the vector of the tip approaching the surface is perpendicular to the surface [3].

When performing measurements, compensation for the radius of the measuring sphere of the tip is mandatory. At the moment the sphere touches the surface, a mathematical shift in the measured coordinates occurs by the value of the probe radius. The direction of the shift is selected automatically by the software of the coordinate measuring machine.

The accuracy of measurements is greatly affected by the speed of movement of the measuring tip at the moment it touches the surface of the part. For example, according to the recommendations of Renishaw, the optimal speed of movement for most measuring sensors should be in the range from 0.5 mm/s to 40 mm/s. A speed of less than 0.5 mm/s leads to a decrease in accuracy due to malfunctions in the sensor trigger system and the occurrence of false alarms. Speeds above 40 mm/s reduce the measurement performance due to the presence of a shift in the contact point

as a result of the inertial overrun of this point. For the present measurements, a contact-speed range of 2 to 10 mm/s was selected [4]. Considering the possible breadth of the range of controlled parts, which can differ significantly from each other in their configuration, dimensions and requirements for the accuracy of dimensions and relative position of surfaces, modern coordinate measuring machines implement several measurement control modes. Manual and programmed control modes are distinguished [5]. These modes determine the method and level of interaction between the operator and the coordinate measuring machine. It is worth noting that the paper considers coordinate measuring machines equipped with servo drives with numerical control of the axes.

The manual mode of control of the coordinate measuring machine is the simplest. It assumes completely manual control of all movements by the operator. In this case, measurements are carried out sequentially point by point without pre-developed programs [6]. Registration of measurement results is carried out when the measuring tip touches the surface.

The advantages of using the manual mode are:

- no need for programming;
- applicability to individual parts, including those with a complex surface;
- low cost of measurements;
- low labor costs.

The disadvantages of the manual mode of control of the coordinate measuring machine are:

- low measurement productivity;
- increased measurement error due to the human factor (the operator does not always optimally select the speed of movement when touching the measured surface, and the direction of the motion vector of the measuring tip may differ from the normal to the surface by more than $\pm 20^\circ$);

- difficulty in maintaining repeatable probe trajectories when measuring complex geometry [7].

Most often, the manual mode is used to measure parts that consist of the simplest geometric elements. In this case, it is easier to determine the correct approach vectors to the surface. It is also possible to use it to control parts with complex geometry for which a solid 3D model is not available.

The main recommendation when using the manual control method is to select the points that are most distant from each other when measuring a specific surface. This minimizes the ambiguity of the position of the geometric element. The main advantage of using coordinate measuring machines equipped with numerical control is the minimization of the human factor by automating the measurement process. Automation is achieved by creating a control program. The programmed control mode of the coordinate measuring machine is characterized by the following advantages:

- automation of the measurement process;
- the ability to use a solid 3D model to create a control program;
- high-precision measurements of complex surfaces;
- high measurement productivity;
- minimization of the human factor.

The disadvantages of the programmed control method are:

- high labor costs for creating a control program;
- complexity of implementing processes for measuring new parts;
- high requirements for operator qualifications.

High qualification requirements for the operator in the context of manual coordinate measuring machine (CMM) operation should be understood as a set of specialized competencies that directly affect measurement accuracy and repeatability.

First, it is critically important to understand the principles of orienting the probe relative to the surface normal. Even slight deviations in the probe approach vector can lead to significant coordinate errors.

Second, the operator must possess precise manual control skills for probe movement speed, especially in the contact zone. Insufficient smoothness or exceeding the allowable speed may result in inertial slipping of the stylus tip and distortion of the measured value.

Third, confident proficiency in fixturing methods based on the 3-2-1 system is required, including knowledge of positional tolerances for base elements and the ability to minimize the influence of residual play or misalignment during part clamping on the machine table.

Finally, the operator must be familiar with the geometry of the inspected component and be able to interpret the measurement results with consideration of potential deformations, form deviations, and applicable technological specifications. The absence of any of these skills significantly reduces the reliability of data obtained in manual mode.

The programmed method of coordinate measuring machine control is used to check serial parts, as well as in cases where high-precision measurements of important individual products are required. Programming is performed in the Dimensional Measuring Interface Standard language, which is a standard control language for coordinate measuring machines.

The structure of the Dimensional Measuring Interface Standard program consists of several key blocks located in a certain regulated sequence.

- Definition of the part coordinate system;
- Description of geometric elements;
- Measurements;
- Setting tolerances and checking the conformity of the measured dimensions;
- Report generation.

When sequentially measuring several surfaces of one part, the group of blocks 2 - 4 is repeated. The commands that ensure the formation of the report can be specified both after each cycle of surface measurements and at the end of all measurements.

The commands that ensure the performance of surface measurements include a number of process parameters that describe the normals of approach to the surface and the speed of movement of the probe. This allows for high-precision measurements [8].

The software of coordinate measuring machines also has the ability to implement a self-learning mode. In this mode, the probe movement is controlled manually, but there is also the ability to simultaneously record the coordinates of points and commands into the control program. This allows for the optimization of the process of programming measurements of complex products that do not have a 3D model. The machine has the ability to recognize geometric elements and calculate the vectors for bringing the probe to the surface. Also, in the self-learning mode, the number of points for measuring specific surfaces can be set. That is, this process uses predefined algorithms to optimize measurement parameters (trajectories, touch points, speed, number of measurements, normal vector correction, etc.) based on the data obtained as a result of measurements in manual control mode. The purpose of this study is to determine the values of deviations from nominal dimensions when measuring a circle depending on the method of controlling a coordinate measuring machine. The paper examines manual and programmed control methods when measuring.

2. Materials and methods

The measurements were carried out using a coordinate measuring machine (CMM) Mezorix Atlas C 686 Basic, equipped with computer numerical control and servo drives along all axes. The main metrological characteristics of the machine comply with ISO 10360 standards: the maximum permissible error in length measurement (MPE_E) does not exceed $2.6 + L/300 \mu\text{m}$, and the maximum permissible probing error (MPE_P) does not exceed $2.4 \mu\text{m}$. The working volume of the machine is limited to coordinates of $600 \times 800 \times 600 \text{ mm (X} \times \text{Y} \times \text{Z)}$, which meets the dimensional requirements for typical diesel engine components.

A Renishaw TP20 touch-trigger probe with a standard force module was used as the measuring element. The diameter of the stylus ball was 4 mm, and the length of the stylus shaft from the ball center to the mounting point was 40 mm. The probe was mounted on a PH10T motorized indexing head, enabling angular orientation adjustments along axes A and B in 7.5° increments. Two positions were used during measurements: $A = +45^\circ$; $B = +90^\circ$ and $A = +45^\circ$; $B = -90^\circ$, allowing access to opposite sides of the piston's cylindrical surface.

Prior to the measurements, spatial probe calibration was performed in each of the utilized positions in accordance with the CMM manufacturer's recommendations. Additionally, a repeatability check was conducted to confirm the stability of contact points.

Measurements were carried out in a dedicated metrology room with controlled climate conditions. The ambient temperature was maintained at $(20 \pm 0.5)^\circ\text{C}$, and the relative humidity did not exceed 50%. Before measurement, the piston underwent thermal stabilization for 4 hours to equilibrate with the laboratory environment, in accordance with GOST 8.563 and ISO 1 standards. This ensured the minimization of thermal expansion and eliminated temperature-induced errors that could affect high-precision measurement results.

The specified parameters of the experimental setup ensured a high level of reproducibility and objectivity of the acquired data, and enabled accurate comparison of results obtained in manual and programmed CMM operating modes.

The object of the study was a piston of a Cummins diesel internal combustion engine. For the study, it is proposed to measure the piston diameter in the measurement zone located at a distance of 119 mm from the end of the piston skirt. The measurement scheme is shown in Fig. 4. The diameter is measured in three sections, the middle of which is parallel to the axis of the hole for the piston pin, and the remaining two sections are at an angle of $\pm 3^\circ$ to the first section. This measurement scheme is due to the features of the automated control line at the manufacturing plant producing these pistons.

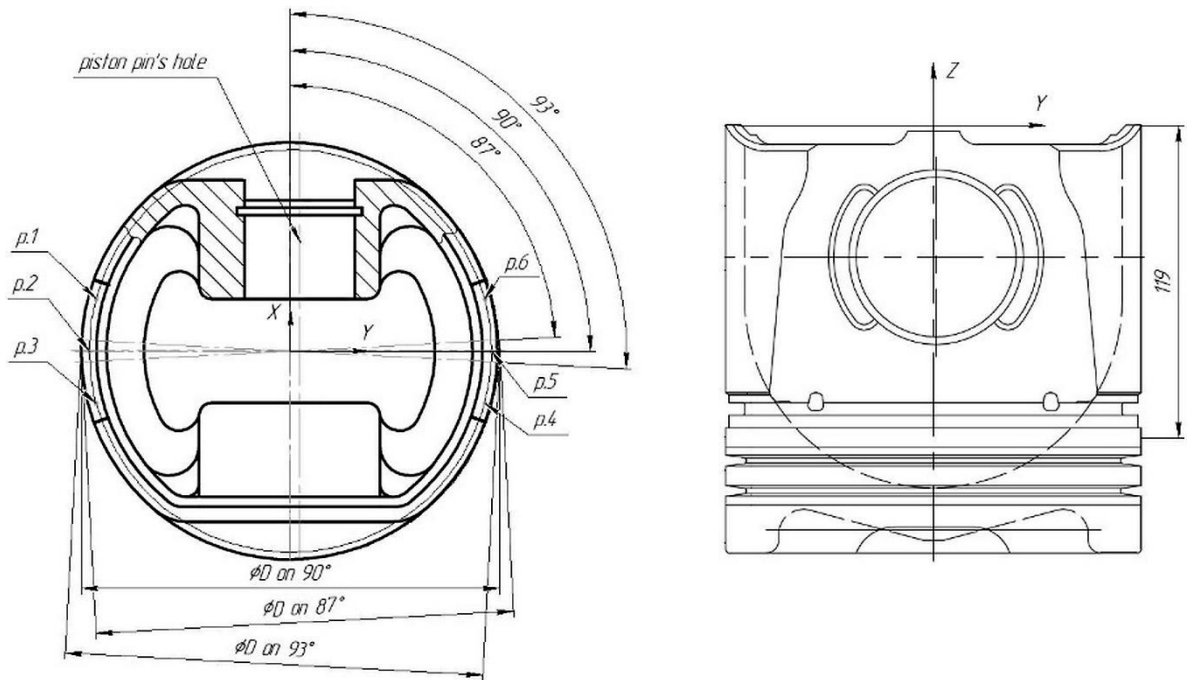


Fig. 4. - Piston-diameter measurement diagram: p.1-p.6 - measurement points in the specified section. Source: compiled by the authors.

The experimental procedure comprised three successive stages. First, the piston was fixtured on the CMM table. Second, the workpiece coordinate system was established. Third, the target diameter was measured first in manual mode and then in programmed mode.

At the basing stage, the piston was installed in the working volume of the coordinate measuring machine so that its axis was directed parallel to the Z axis of the machine, and the axis of the holes for the piston pin was parallel to the X axis. The basing was carried out on three point supports located under the piston bottom and an additional double guide base, ensuring the correct rotation of the piston around the Z axis (Fig. 5). This arrangement of the piston in space provides convenient access to the measured surfaces, and also allows you to set the coordinate system relative to the base surfaces.

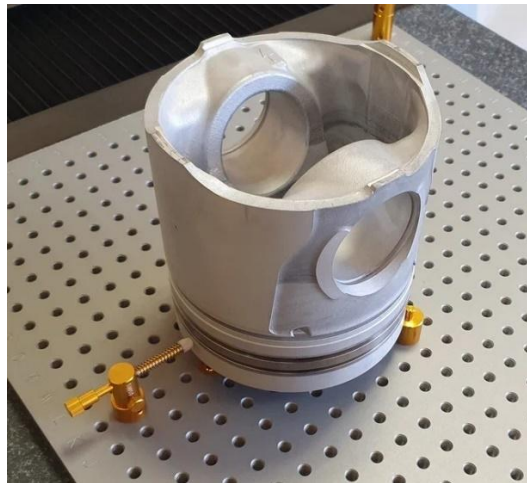


Fig. 5. - Cummins engine piston mounted on the coordinate measuring machine table. Source: compiled by the authors.

The coordinate system at the second stage was set in several successive steps according to the 3-2-1 system (plane, line, point).

Defining the base plane passing through the end surface of the piston skirt. This decision was made due to the specifics of setting the geometric dimensions on the design drawing of the part. The measurement was first carried out in manual mode with self-learning enabled (the software recorded the coordinates of the measured points and the approach vectors to them). Then, after creating a nominal plane passing through six measured points p.1 - p.6, the probe approach vectors and the speed of movement upon contact were adjusted in the software. A repeated

measurement of the base plane was carried out in the programmed mode to improve the accuracy of the measurements.

To set the direction of the X axis of the part coordinate system taking into account the requirements for carrying out measurements, the axis of the hole for the piston pin was measured. The measurements were also preliminarily carried out in manual mode with self-learning of the machine, and then re-measured in the programmed mode according to the calculated approach vectors and speed of movement.

To set the center of coordinates, the circumference was measured in one of the piston belts between the first and second compression rings. The circumference was measured at 6 points located approximately at the same distance from each other on the same diameter. The nominal circumference was determined in the software, and 6 points equally spaced along the circumference were programmed. As a result of the calculation, the approach vectors and the speed of movement were adjusted. Based on the results of repeated measurements in the programmed mode, the point of the center of coordinates of the part was calculated.

At the final step, the coordinate system of the part was combined with the machine coordinate system. This simplified the calculations carried out in the future.

Thus, due to the fact that the part will not be re-based, and the coordinate system is set once for both methods of controlling the coordinate measuring machine, this will not have an additional effect on the differences in the measurement results obtained in the third stage in the manual and programmed measurement modes.

The third stage of measurements was carried out separately in the manual mode, and then in the programmed mode. Let us consider the measurement technique in the manual control mode. Taking into account the performed alignment of the machine coordinate system and the part coordinate system, all movements were set manually via the joystick. For this purpose, the measuring head was initially rotated by an angle of $A = +45^\circ$ $B = 90^\circ$ in order to ensure that the probe tip touched the specified points. It should be noted that before the start of the study, the probe was calibrated in all positions in space required for testing (different angles A and B).

After selecting the required probe position, the measuring probe was moved to the height mark $Z = -119$ mm, which meets the requirements of the measurement scheme. Measurements were taken at three points. The probe of the coordinate measuring machine was moved to a safe distance, after which the position of the measuring head was changed to angles $A = +45^\circ$ $B = -90^\circ$. Measurements were taken at the last three control points.

Since the points are located at an extremely small distance from each other when taking measurements according to the scheme shown in Fig. 4, it is not possible to determine and visually correct the approach vector in manual mode. Therefore, all measurements were taken in the direction parallel to the Y axis of the part. The speed control on the joystick was set with a limit of 10 mm/s. Based on the measurement results, the diameter of the circle in the required measurement zone was calculated.

To take measurements in programmed mode, it was initially necessary to create a control program. In the RationalDMIS software, program code can be created in two ways - by manually writing a text file with commands and developing a program based on a preliminary code obtained during self-learning.

In the case of manual code writing, it is necessary to take into account the idle stroke of the measuring head, which is always performed along the shortest path between two points. This prevents the measuring head from colliding with the part or technological equipment. If the operator does not have sufficient experience to write code manually, it is allowed to use the self-learning mode. The advantage of this method is the ability to pre-determine the trajectories of idle movements.

2. Results

Below is a comparison of the code commands obtained as a result of manual mode with self-learning mode enabled and programmed mode, with adjusted normal vectors of approach to measurement points.

Part of the code obtained with manual control with self-learning:

```
UNITS/MM, ANGDM, MMPS
MODE/MAN
....
F(CIR5_L119)=FEAT/CIRCLE,OUTER,CART, -0.113, 1.038 -119.012,0.000,-0.000,1.000, 157.782
MEAS/CIRCLE, F(CIR5_L119), 6
  SNLCT/S(D4X40_A45_B90)
    PTMEAS/CART, -79.172, 4.149, -119.000, -1.000, 0.000, 0.000
    PTMEAS/CART, -79.281, 0.000, -119.000, -1.000, 0.000, 0.000
    PTMEAS/CART, -79.172, -4.149, -119.000, -1.000, -0.000, 0.000
  SNLCT/S(D4X40_A45_NB90)
....
    PTMEAS/CART, 79.172, -4.149, -119.000, 1.000, 0.000, 0.000
    PTMEAS/CART, 79.281, 0.000, -119.000, 1.000, 0.000, 0.000
    PTMEAS/CART, 79.172, 4.149, -119.000, 1.000, 0.000, 0.000
```

Code obtained by programming:

```
UNITS/MM, ANGDM, MMPS
MODE/PROG,MAN
...
```

```

F(CIR5_L119)=FEAT/CIRCLE, OUTER, CART, 0.000, 0.000, -119.000, 0.000, -0.000, 1.000, 157.782
MEAS/CIRCLE, F(CIR5_L119), 6
SNSLCT/S(D4X40_A45_B90)
PTMEAS/CART, -79.172, 4.149, -119.000, -0.999, 0.052, 0.000
PTMEAS/CART, -79.281, 0.000, -119.000, -1.000, 0.000, 0.000
PTMEAS/CART, -79.172, -4.149, -119.000, -0.999, -0.052, 0.000
SNSLCT/S(D4X40_A45_NB90)
.....
PTMEAS/CART, 79.172, -4.149, -119.000, 0.999, -0.052, 0.000
PTMEAS/CART, 79.281, 0.000, -119.000, 1.000, 0.000, 0.000
PTMEAS/CART, 79.172, 4.149, -119.000, 0.999, 0.052, 0.000

```

The measurement results are shown in Table 1.

Table 1. Results of piston-diameter measurements

Parameter	Manual measurement	Programmed measurement
Nominal diameter according to drawing, mm	157.782	
Maximum deviations according to the drawing, mm	±0.08	
Nominal element	circle	circle
Actual size, mm	157.7377	157.7550
Actual deviation, mm	-0.0443	-0.0270

Source: compiled by the authors.

In addition to the numerical values presented in Table 1, it is important to highlight the nature of the point distribution recorded in each measurement mode. In manual CMM operation mode, a greater dispersion of the measured point coordinates relative to the nominal circle was observed, indicating variability in probe contacts due to the inability to precisely control the approach vector direction and maintain consistent movement speed. In practice, this results in increased ellipticity of the calculated circular profile and a rise in the standard deviation of point coordinates.

In contrast, the programmed mode showed more uniform deviations symmetrically distributed about the center, indicating stable orthogonality of probe contacts and high contact reproducibility. These observations confirm that the trajectory and angular precision of probe approach significantly affect the final diameter measurement value.

To increase the statistical reliability of the conducted study, a series of repeated measurements of the target piston diameter of a Cummins diesel engine was performed using two coordinate measuring machine (CMM) operating modes: manual and programmed. In each mode, 10 measurements of the same diameter were carried out. The measurement results were subjected to statistical analysis, including the calculation of standard deviation (σ), range (R), and measurement uncertainty (U).

The results are presented in Tables 2 and 3.

Table 2. Repeated piston-diameter measurements

Experiment number	Programmed mode, mm	Manual mode, mm
1.	157.7554	157.7356
2.	157.7546	157.7355
3.	157.7556	157.7396
4.	157.7566	157.7273
5.	157.7545	157.7284
6.	157.7545	157.7362
7.	157.7564	157.7415
8.	157.7557	157.7393
9.	157.7543	157.7407
10.	157.7548	157.7377

Source: compiled by the authors.

Table 3. Statistical characteristics of piston-diameter measurements

Measurement mode	Average value, mm	Standard deviation (σ), mm	Range (R), mm	Uncertainty (U), mm
Programmed	157.7548	0.0012	0.0039	± 0.0024
Manual	157.7382	0.0057	0.0191	± 0.0114

Source: compiled by the authors.

In the programmed mode, the evaluated parameters confirm high repeatability and stability of measurement results, all of which remained within the tolerance limits of ± 0.08 mm. In contrast, the significantly higher values of standard deviation (σ) and range (R) observed in the manual mode indicate a pronounced influence of the human factor, primarily associated with inconsistent approach speeds and suboptimal probe approach vectors to the measured surface.

To assess measurement reproducibility, three different operators were involved, each performing a series of five measurements in manual mode. The analysis revealed substantial inter-operator variability: the mean diameter values ranged from 157.7359 mm to 157.7408 mm, while standard deviations varied from 0.0049 mm to 0.0063 mm. In the programmed mode, operator-induced variation was minimal, with mean diameter values ranging from 157.7545 mm to 157.7551 mm and standard deviations between 0.0010 mm and 0.0014 mm. These results underscore the advantage of the automated approach.

Thus, the supplementary experiments confirmed that the programmed CMM operation mode exhibits high repeatability and reproducibility, whereas the manual mode requires a highly skilled operator and results in significant variability in measurement outcomes. The findings of this study provide a well-grounded basis for recommending the programmed CMM mode for serial production and high-precision inspection tasks.

3. Discussion

The analysis of error sources recorded during measurements performed in both manual and programmed modes of coordinate measuring machine (CMM) operation necessitates a comprehensive consideration of the entire set of factors influencing the final deviation from the nominal value. In manual mode, the most significant contribution to the total error arises from the human factor. The key manifestations include deviation of the probe approach vector from the surface normal and instability of approach speed during contact. Even when limiting the speed to 10 mm/s, the operator is not always able to ensure strictly perpendicular contact—particularly in conditions of densely positioned measurement points, where visual vector correction becomes challenging.

An additional source of error is the positioning inaccuracy of the CMM itself, which occurs due to the lack of automatic trajectory error compensation in manual mode. In programmed mode, these errors are substantially minimized thanks to algorithmically calculated probe trajectories based on the nominal geometry of the part.

Thermal effects also impact measurement accuracy—both in terms of thermal expansion of the component and potential thermal drift of the CMM's mechanical elements. However, these factors influence both modes equally and can be considered background variables in the context of this study.

Fixturing error, despite the use of a consistent 3-2-1 method and the absence of reclamping, may result in localized micromovements during manual setup due to contact forces, especially during the initial self-learning phase.

Finally, stylus calibration in various spatial orientations is essential but not absolute. Minor deviations in compensation radius at different angular positions can also affect accuracy, particularly in manual mode, where contact repeatability is lower.

Both measurement results remained within the specified tolerance of ± 0.08 mm. The programmed mode yielded an actual deviation of -0.0270 mm, whereas the manual mode yielded -0.0443 mm. Accordingly, programmed control reduced the absolute deviation from the nominal diameter by 39.1%. The programmed result therefore provides a larger tolerance reserve, which is important for serial inspection because it reduces the probability of false rejection and repeated measurement.

The repeated-measurement series supports the same conclusion. The mean values obtained in programmed and manual modes were 157.7548 and 157.7382 mm, corresponding to deviations from the nominal diameter of -0.0272 and -0.0438 mm, respectively. The standard deviation decreased from 0.0057 mm in manual mode to 0.0012 mm in programmed mode, while the uncertainty decreased from ± 0.0114 to ± 0.0024 mm.

The 4.75-fold reduction in both standard deviation and uncertainty demonstrates the higher repeatability and stability of programmed measurements. These results are consistent with the metrological characteristics of the Mezorix Atlas C 686 Basic CMM and confirm that trajectory control has a stronger effect on result dispersion than on the systematic difference between the measured and nominal diameters.

The programmed measurement routine contains approach vectors (I, J, K) refined according to the nominal geometry. Although the vector values differ only slightly between manual measurement ($-1.000, 0.000, 0.000$) and programmed measurement ($-0.999, 0.052, 0.000$), the correction aligns the probe motion more closely with the surface

normal. In manual mode, the proximity of the control points prevents reliable visual correction of the approach direction. The self-learning mode is therefore useful for generating an initial program and recording collision-free intermediate trajectories, after which the approach vectors and contact speed should be optimized in RationalDMIS. Self-learning does not eliminate operator-induced variation during manual probing. The combined procedure preserves the practical advantages of manual trajectory definition while providing the repeatability of programmed control. The unchanged 3-2-1 fixturing scheme and the single workpiece coordinate-system setup excluded re-fixturing error from the comparison.

The novelty of this study lies in the comprehensive evaluation of coordinate measurement accuracy during inspection of the cylindrical surface of a diesel engine piston, specifically in a zone defined by the production process (at a distance of 119 mm from the piston skirt), utilizing both programmed and manual CMM modes, including the self-learning mode. Unlike previously published works, which focused on the measurement of simple geometric elements under laboratory conditions or with complete CAD modeling, the present study implements a hybrid approach: the measurement program is generated programmatically based on trajectories initially obtained in manual mode using the built-in self-learning algorithm.

A distinctive feature of the experiment is the execution of measurements in a zone with limited visualization and densely arranged control points, where visual correction of the probe approach vector in manual mode is virtually impossible. In this context, for the first time, a qualitative comparison has been conducted between the effects of nominal approach vectors calculated via self-learning and those defined manually by the operator. The analysis provides a quantitative assessment of the advantages of the programmed mode with refined approach parameters under conditions of high-precision inspection of a typical precision-manufactured component.

Thus, the contribution of this work extends beyond empirical comparison of the two CMM control modes; it demonstrates the practical significance of self-learning algorithms as an intermediate stage in the development of measurement routines in the absence of a CAD model - an aspect that has not been sufficiently addressed in existing scientific literature.

Conclusions

The use of the programmed control mode of a coordinate measuring machine is preferable when solving problems that require high accuracy and repeatability of results, as well as in the case of use in serial production. The manual control mode with self-learning enabled is proposed to be used to obtain the initial code taking into account the trajectories of the part and technological equipment during the measurement process. It is also possible to use it when checking non-standard parts for which the development of a full-fledged measurement control program is impractical for economic and time reasons. In addition, it can be reliably stated that obtaining accurate measurement results in manual mode requires a highly qualified operator.

Based on the results obtained, the following recommendations are proposed to ensure the most accurate measurement results:

1. Priority selection of the programmed mode.
2. Use of data obtained in the self-learning mode to minimize the time spent on program development.
3. Control of the probe approach speed and the direction of approach to the surface.
4. Training coordinate measuring machine operators in new methods.

The self-learning mode is a convenient tool for obtaining initial data for developing a control program for coordinate measuring machines.

The practical significance of the study lies in the developed recommendations for selecting control modes for a coordinate measuring machine, taking into account the type of production and requirements for measurement accuracy. The results obtained can be applied to real manufacturing enterprises that carry out quality control using CMMs.

Further research can be aimed at optimizing the time spent on measurements and drawing up control programs for CMMs. Also promising is the analysis of the possibility of drawing up control programs using the capabilities of artificial intelligence [9, 10]. These areas of further research will improve the efficiency of using coordinate measuring machines and significantly simplify the implementation of automated solutions in production.

Programmed control increased measurement quality in two complementary respects. The absolute deviation from the nominal diameter decreased from 0.0443 to 0.0270 mm, corresponding to a 39.1% reduction, while the standard deviation decreased from 0.0057 to 0.0012 mm, corresponding to a 4.75-fold improvement in repeatability. These effects provide a larger tolerance reserve and reduce the likelihood of inspection errors in serial production.

The obtained results demonstrate that the application of optimized approach algorithms (in terms of vector direction and speed) can significantly improve measurement quality even in the absence of a complete CAD model. Moreover, the use of self-learning mode proves to be an effective tool for accelerated generation of measurement programs.

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Information of the authors

Nefelov Ilya, State University of Management

e-mail: nefelov.sum@bk.ru

Filatov Vladimir, State University of Management

e-mail: filatov.isc@bk.ru

Taldykin Dmitriy, State University of Management

e-mail: taldykin.sum@bk.ru