STUDY ON GEOMETRIC ADVANCED CONTROL OF ACTUAL MACHINED PRODUCT FEATURES

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A comparative analysis to evaluate two different measurement systems within industrial applications has been unrolled, particularly in the context of part complex geometry. The findings reveal differences in measurement performance, highlighting some advantages and limitations of the CMM and 3D Scanner, respectively, mainly in terms of precision and data acquisition time. This study offers valuable insights into the selection of appropriate metrological tools based on specific product requirements, contributing to the optimization of quality control processes in engineering within industrial contexts.

Keywords: Coordinate Measuring Machine (CMM), 3D Scanner, quality control, dimensional accuracy, precision measurement, measurement uncertainty, industrial application.

1. Introduction

In manufacturing and quality control processes, the demand of high precision and reliable dimensional measurements is paramount.

As industries strive to ensure product quality and performance, the use of advanced control systems including a Coordinate Measuring Machine (CMM) and/or a 3D Optical Scanner has become increasingly widespread; these are recognized for their accuracy to measure, with some specific particularities, intricate geometries; the challenge lies in determining their relevant performance characteristics in diverse practical applications.

In order to improve the accuracy of a CMM, a method for geometric error identification based on spatially integrated measurement is developed, and its validity is verified through simulation and experiments [1].

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[◊] This paper is drawn up to be presented, as appropriate, in a section of ICAMaT 2024

The assessment of measurement uncertainty is critical in ensuring reliable measurement results. Various approaches were applied to evaluate uncertainty of CMM measurements, emphasizing the need for standardized methods to achieve consistency and reliability across different tasks [2].

Comprehensive guidelines for the expression of measurement uncertainty are in place, highlighting its importance in the accurate evaluation of measurement systems [3].

In order to examine the performance of a CMM, an experimental test pattern was measured using CMM in laboratory conditions, and then in a workshop - equipped with temperature compensation system. The measurement results were analyzed to verify repeatability and reproducibility of CMM, the parameters which are important in industrial production [4].

3D optical scanning technologies have emerged as powerful tools for high-precision 3D reconstruction and surface analysis. The effectiveness of 3D optical scanning for reconstructing small-sized objects was demonstrated, offering insights into its application in cultural heritage and other fields requiring detailed surface data [5].

The application of optical triangulation method to investigate the shape and wear of cutting inserts illustrates the potential of 3D optical scanners for accurate and detailed measurements in industrial applications [6].

A 3D printed product made of PLA polymer was analysed using, for geometric control, a CMM and a measuring scanner. This was based on 3D CAD product model as a reference basis for measuring deviations of the actual part. In relation with each of CMM and a measuring scanner, respectively, a series of technological procedural elements of measurement are revealed in correspondence with particularities of geometric characteristics of different part surfaces - small diameters, deep holes, etc. [7].

A pneumatic measurement method is developed to measure characteristics of a inner cylindrical surface, including evaluation of diameter and roundness measurement uncertainty, providing valuable insights into methodologies for dimensional control in industrial sites [8].

A multi-objective optimization of roundness and positional errors in laser cutting of holes in stainless steel is developed, offering useful perspectives on the correlation between manufacturing processes and metrological accuracy [9].

The present study conducts a measurement process on a real machined part using a CMM with a touch trigger probe and a 3D optical scanner, respectively, by focusing on dimensional and form accuracy. The findings contribute to a deeper understanding of how these systems perform in real-world applications, assisting manufacturers and quality control professionals in making informed decisions to optimize their measurement processes.

2. Methodology

2.1. *Machined part specifications*

The machined part (Fig. 1), used for this study, is fabricated from Al7075-T351, a high-strength aluminium alloy. With superior mechanical properties, as high corrosion resistance and good machinability, Al7075-T351 is considered, e.g., in aerospace and automotive applications.

The main prescribed geometric features of the considered part are as presented in Fig. 2. These include critical features such: inner and outer diameter tolerances, bore cylindricity tolerance, flatness tolerance, runouts tolerances, O-ring channel dimensions, etc.

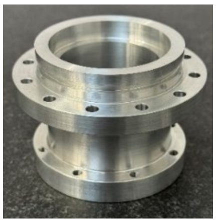

Fig. 1. Machined part

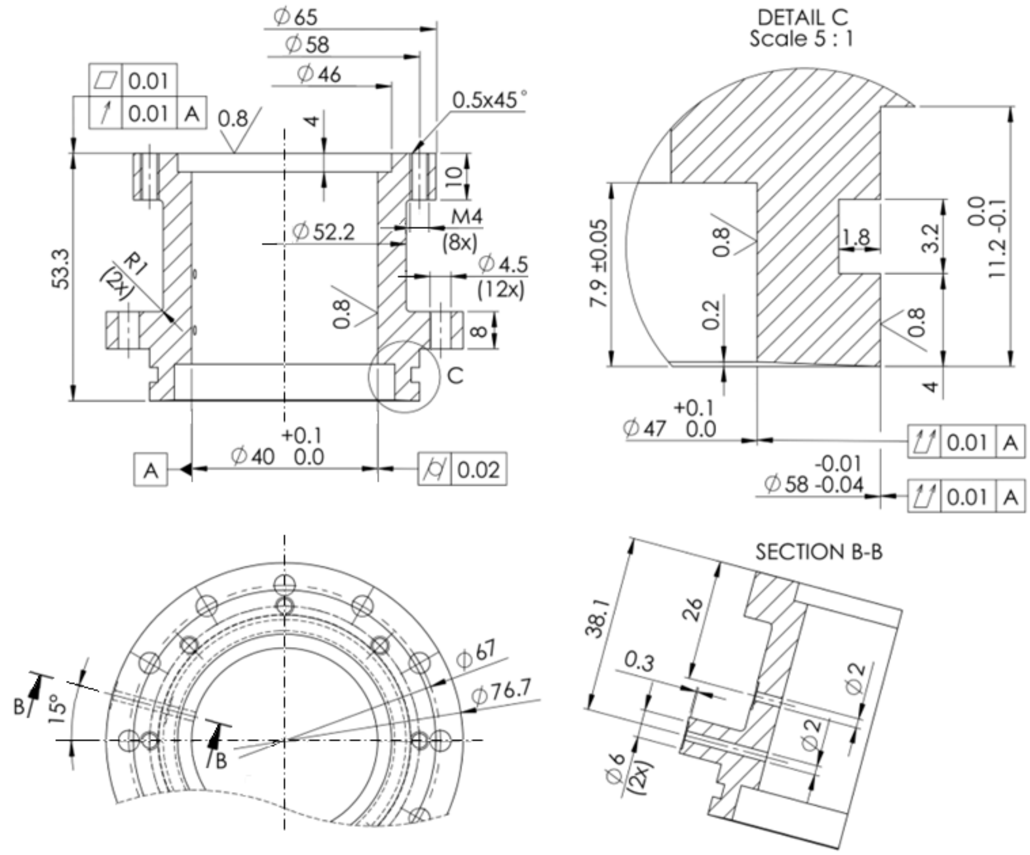

Fig. 2. Machined part main geometric features

2.2. *Technological control systems*

The geometric control of the machined part was performed using two different systems: a CMM System, that mainly includes a 10.10.8 Coordinate Measuring Machine (Fig. 3) probe equipped with a monitored indexing head having a 2 x 21 sapphire stylus (Fig. 4); a Scanner System, consisting in a 3D optical scanner equipped with 300/MV150 objective lenses (Fig. 5).

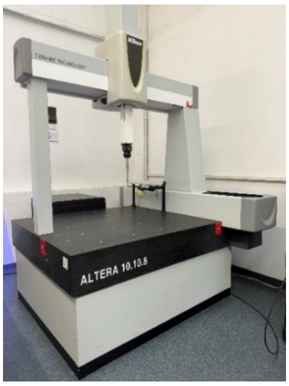

Fig. 3. 10.10.8 Coordinate measuring machine

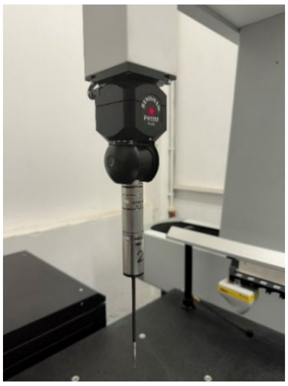

Fig. 4. Indexing probe head

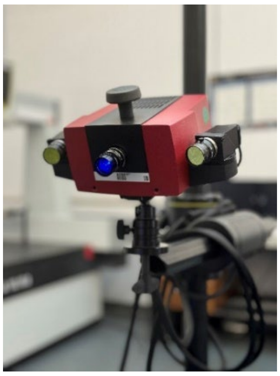

Fig. 5. 3D optical scanning system

(1) CMM setup

The 10.10.8 CMM offers a high level of precision with a volumetric accuracy of 2.0 µm + L/400 mm, making it suitable for high precision dimensional measurement tasks. The machine is configured with a measuring range of 1000 x 1000 x 800 mm, providing sufficient coverage for the part being measured. The indexing probe head is a monitored one that allows precise indexing of the stylus at various angles, ensuring optimal access to different features of the machined part. This flexibility is particularly useful for measuring complex geometries and hard-to-reach areas. A 2 x 21 sapphire stylus (2 mm diameter and 21 mm length), is utilized for its hardness and wear resistance, making it ideal for probing the aluminium alloy without damaging the part surface.

(2) 3D optical scanner setup

The 3D optical scanner is a high-resolution structured light system designed for non-contact measurement. It utilizes blue light technology to capture accurate 3D data across complex geometries. The scanner offers a point spacing of up to 0.02 mm, ensuring fine detail capture of small features and freeform surfaces. 300/MV/150 objective lenses are optimized for capturing broader surface areas.

These are typically used for scanning larger portions of the machined part ensuring accurate data collection over more extensive areas. The scanner was calibrated according to the manufacturer's guidelines before each session to ensure maximum accuracy. The part was positioned on a rotary table, allowing for multiple scans from different angles, which were later merged to form a complete 3D model.

It is to be noted that both systems were set up in a controlled environment with a constant temperature of 20 ± 1°C.

2.3. *Data acquisition process*

<u>CMM data acquisition</u>

Probe calibration. The probe head and sapphire stylus were calibrated to ensure accuracy. This involved probing a reference sphere at known locations.

Measurement strategy. The machined part was secured using a fixture, to prevent movement during measurement, and placed on the CMM granite table (Fig. 6). The probe was programmed to measure the considered features.

Fig. 6. Part fixture

Tactile probing. For each feature, the stylus made contact at predefined part points, recording the coordinates. Then, the CMM software (CAMIO) calculated the actual dimensional values and/ or the actual deviations with respect to the correspondent nominal values.

<u>3D Scanner data acquisition process</u>

Part preparation. The machined part was coated with a matte spray of titan dioxide to eliminate reflections and evenly distribute some markers across the part surface to improve the scanner ability to capture accurate surface data. It should be noted that this preparation of the piece is a time-consuming activity.

Scanning process. The 3D scanner captured multiple views of the part by projecting structured light onto its surface. As the part rotated on the table, the scanner collected high-resolution point clouds from different angles.

Data merging. After all views were scanned, the individual point clouds were merged to create a full 3D digital model part. The software automatically aligned the scans based on common reference points and generated a complete, accurate surface profile.

Feature extraction. Key features were extracted from 3D model.

3. Technological control operation

3.1. Relationships and procedural steps

Within the considered machined part (Fig. 2): a prescribed dimensional characteristic is defined by its nominal value, the upper and lower deviations; the prescribed form and relative position features have the significance according to ISO 1101:2017 [10].

Regarding a prescribed dimensional characteristic L, the actual values L_k and the correspondent actual deviations E_k are determined by calculus based upon certain measured elements, where E_k are defined with respect to nominal value, L_N, i.e.,

$$E_k = L_k - L_N, \; k = 1, 2, \ldots, \text{k} = \text{i, j, etc., as the case} \quad (1)$$

The actual form and relative position deviations are determined by calculus based upon certain measured elements, according to the working procedures within the operating technological control system.

From the technological control process of the machined part (Fig. 2), the operation further considered refers to the actual diameter and actual cylindricity of the inner cylinder with prescribed diameter of $\varnothing\, 40^{0.1}$mm and cylindricity tolerance of 0.02 mm.

The practical relevant procedural steps, which are specific to the CMM System and the 3D Scanner System, respectively, are as follows.

Within the CMM System, the measurements were performed at five axial positions along the considered inner cylinder, starting from the z = 0 origin. For each position, z = 0, 2, 4, 16, 32 mm, 10 equidistant points of the considered surface were contacted, and their coordinates were recorded. These points were used to construct a best-fit circle at each z position (Fig. 3), enabling the determination of the circle actual diameter and actual circularity deviation, as well as the center coordinates (x, y, z) of each circle, the diameter and the cylindricity deviation of the considered actual inner cylinder.

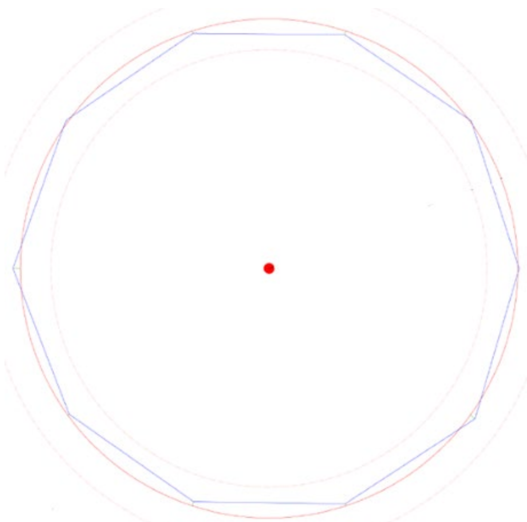

Fig. 3. A best-fit circle at certain z position within CMM System

Within 3D Scanner System, a complete scan of the considered inner cylinder was performed. The resulting point cloud was processed to extract slices at the same axial positions (z = 0, 2, 4, 8, 16, 32 mm) as in CMM measurements. Each slice was analyzed to determine the cylinder axis coordinates, diameter, circularity and cylindricity. The part dimensional accuracy is evaluated by comparing the reconstructed model to the nominal CAD model (Fig. 4).

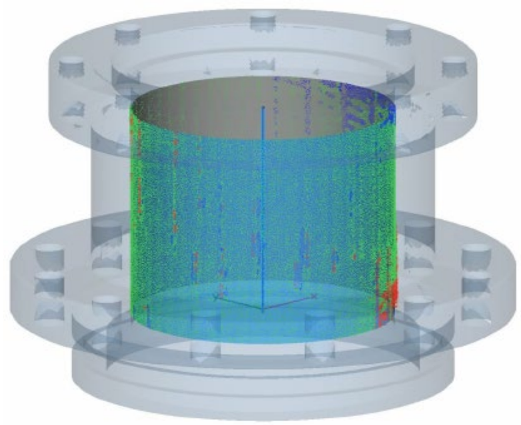

Fig. 4. The rendered point cloud within 3D Scanner System

In order to evaluate the uncertainty of measurement results [3, 11], a repeatability process of low volume is performed, and the sample standard deviation is associated, as follows.

Within CMM System and upon the considered machined part, at z position, z = 8 mm, the determination of the diameter, *D*, and circularity deviation, *C*, is repeated through five trials, $i = \overline{1,5}$, and if the actual determined values are Y_{j_i}, then the average value, $\bar{Y}_j$, and the sample standard deviation, $s\ (Y_j)$, are:

$$\bar{Y}_j = \frac{1}{n}\sum_{i=1}^{n} Y_{j_i},\ n = 5,\ Y_1 = D, Y_2 = C \quad (2)$$

$$s\ (Y_j) = \sqrt{\frac{\sum_{j=1}^{n}(Y_{j_i} - \bar{Y}_j)^2}{n-1}},\ n = 5,\ Y_1 = D, Y_2 = C \quad (3)$$

In this study, the uncertainty of the average value, $\boldsymbol{u(\bar{Y}_j)}$, is taken into account, i.e.,

$$u\ (\bar{Y}_j) = s\ (Y_j)/\sqrt{n},\ n = 5,\ Y_1 = D, Y_2 = C \quad (4)$$

3.2. Experimental results

The considered technological control operation was carried out, according to the elements presented in § 2.4.

The actual values of the diameter, diameter deviation, circularity deviation and of circles centers coordinates, which were obtained by using of CMM System and 3D Scanner System, are presented in Table 1 and Table 2, respectively.

Table 1

Actual (measured) diameters and diameter deviations

z position, mm	Prescribed diameter, mm	CMM System		3D Scanner System	
		Actual diameter, mm	Actual diameter deviation, mm	Actual diameter, mm	Actual diameter deviation, mm
0	$Ø\ 40^{0.1}$	40.0707	0.0707	40.061	0.061
2		40.0705	0.0705	40.063	0.063
4		40.0714	0.0714	40.063	0.063
8		40.0725	0.0725	40.062	0.062
16		40.0679	0.0679	40.069	0.069
32		40.0648	0.0648	40.067	0.067

Table 2

Actual circularity deviations and the coordinates (x, y) of the actual circles′ centers

z position, mm	Prescribed cylindricity tolerance, mm	CMM System			3D Scanner System		
		Actual circularity deviation, mm	x, mm	y, mm	Actual circularity deviation, mm	x, mm	y, mm
0	0.02	0.0059	0.0002	-0.0027	0.008	0	0
2		0.0050	-0.0012	-0.0039	0.007	0	0
4		0.0083	-0.0013	-0.0029	0.011	0	0
8		0.0058	-0.0017	-0.0032	0.015	0	0
16		0.0050	-0.0024	-0.0031	0.045	0.001	-0.001
32		0.0067	-0.0047	-0.003	0.050	0	0

Furthermore, the actual inner cylinder was configured, and its main characteristics are presented in Table 3.

Table 3

Diameter and cylindricity deviation of the actual inner cylinder

z position, mm	Prescribed diameter, mm; cylindricity tolerance, mm	CMM System		3D Scanner System	
		Actual diameter, mm	Actual cylindricity deviation, mm	Actual diameter, mm	Actual cylindricity deviation, mm
[0; 32]	$Ø\ 40^{0.1}$; 0.02	40.066	0.0105	40.063	0.026

Also, the actual values of diameter and circularity deviation obtained within the repeatability trials and the other main determination data on the uncertainty of measurement results are presented in Table 4.

Table 4

Uncertainty of measurement results (see eq. 2 – 4)

z position, mm	Prescribed diameter, mm; cylindricity tolerance, mm	CMM System				
		Trial no., i	Actual diameter, mm		Actual circularity deviation, mm	
		1	D_i	40.0725	C_i	0.0058
		2		40.0731		0.0055
		3		40.0732		0.0054
		4		40.0734		0.0055
8	Ø $40^{0.1}$; 0.02	5		40.0734		0.0052
		Average	$\bar{D}$	40.07312	$\bar{C}$	0.00548
		Sample standard deviation	$s\ (D)$	0.00037	$s\ (C)$	0.00021
		Uncertainty	$u\ (D)$	0.00016	$u\ (C)$	0.000096

Based on the above results, the following relevant remarks are to be noted:

• the actual values of the diameter and, implicitly, of the diameter deviation are within the correspondent tolerance field (see Tables 1 - 3);

• the actual values of the diameter and, implicitly, of the diameter deviation which are revealed by the 3D Scanner System are more accurate than those revealed by the CMM System (see Tables 1, 3);

• the actual values of the circularity deviation and of the cylindricity deviation which are revealed by the CMM System are more accurate than those revealed by the 3D Scanner System (see Tables 2, 3);

• the uncertainties of measurement results are of values which are much lower than the tolerances prescribed to the studied diameter and cylindricity deviation, respectively (see Table 4); this demonstrates the high precision of the measurement process unrolled in the present study.

4. Conclusions

Both technological control systems, the CMM System and the 3D Scanner System, are technically suitable for measuring the diameter considered.

3D Scanner System reveals more accurate actual values of diameter and, implicitly, of the diameter deviation.

The CMM System displays slightly higher accuracy for measuring circularity and cylindricity deviations, and also a precise repeatability for both actual diameter and circularity.

The actual diameter and cylindricity deviation of considered machined part are compliant with respect to the correspondent prescribed characteristics.

The measurement process carried out in the present study is of high precision, as proven by the very low values of associated uncertainty relative to the tolerances prescribed to the geometric characteristics which were analysed.

The are premises for further research on operational content including different types of dimensional, form and relative position features.

A broader evaluation of different complex geometrical control systems requires, in perspective, applicative developments of proper techno - economic criteria and norms.

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