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Original scientific paper

The Analysis of Metrological Characteristics of Different Coordinate Measuring Systems

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Abstract: The aim of this paper is to examine the metrological characteristics of some of the most commonly used coordinate measurement systems in industry in a case study of the flatness error. The accuracy and measurement uncertainty of the coordinate measuring machine with contact probe, point by point mode and scanning mode, and with non - contact probe, then performance measuring arm, optical scanner and finally industrial computed tomography were analyzed. In order to exclude factors that affect the accuracy of measurement and measurement uncertainty, and are not part of the hardware structure of the CMS, the experiment was conducted on a reference workpiece and an independent software solution was used to estimate the error of flatness. The accuracy of measuring systems was determined as the difference between the reference value and the mean value of repeated measurements and the measurement uncertainty was determined according to the instructions for estimating the measurement uncertainty GUM. The results of the research showed high metrological performance of the coordinate measuring machine and the optical scanner for this measuring task. Also, it was found that industrial computed tomography gives a very large measurement error and that the measurement uncertainty is very difficult to determine.

Keywords: accuracy; coordinate measurement systems; flatness error measurement uncertainty

1 INTRODUCTION

In the modern industrial world, product quality assessment of dimensional and geometric specifications is mainly performed on coordinate measuring systems (CMS) [1]. The ability to measure all the tolerances indicated on a technical drawing is the main reason why this is so. Also, measuring systems that work on the contact principle and some non-contact ones are characterized by high accuracy, precision and a narrow range of measurement uncertainty [2]. However, due to the possibility of faster measurement, CAD inspection, measurement of inaccessible places on the workpiece or measurement of small objects, the CMS with various non-contact probes is increasingly used. The measurement quality of these measuring systems (accuracy and measurement uncertainty) is lower compared to, for example, coordinate measuring machines (CMM) and also the assessment of measurement quality is often impossible [3].

It is common to all coordinate measuring systems that the measurement process is very complicated and that the measurement result is obtained through two independent phases [4]. The first phase is the physical sampling of data from an object measured by some type of sensors. The real workpiece is translated into a digitized form mainly in the form of a set of coordinates of the sampled points (x, y, z). The second phase is an independent software analysis of the sampled points. The measurement quality parameters will mainly depend on the quality of the first phase, i.e. how much error the measuring system makes in reading the 3D coordinates of the point [5]. The accuracy of determining the position of the sampled points depends primarily on the type of coordinate measuring system (hardware structure), probe system, point sampling mode, etc.

Each measuring system should have a specified measurement quality parameter. The measurement quality parameter must be declared for each measuring system in order to maintain metrological traceability [6]. Measurement accuracy is determined by measuring reference workpieces and measurement uncertainty is specific to the measurement task. Different reference workpieces for accuracy assessment have been developed for different coordinate measuring systems [7]. Also, some procedures are standardized in ISO, ASME and VDI/VDE standards. These standards generally contain procedures for estimating error in measuring reference lengths and for estimating probe error. The accuracy parameters obtained by measuring the reference lengths and measuring the reference hemisphere are generally not sufficient to assess the quality of the measurement, e.g. cylindricality or angle. For this reason, measurement uncertainty must be assessed for each measurement task. For some measurement systems, such as industrial tomography (CT), there are no standardized procedures for assessing accuracy.

Many studies have focused at the determination of metrological characteristics of CMS. In paper [8] the authors present a comparative analysis of five different optical measurement systems (OMS) in purpose Geometric Dimensioning and Tolerancing (GD&T) verification of selective laser melting parts. The results obtained can be served for comparison to OMS in terms of dimensional and geometrical accuracy and inspection speed. Accuracy of different OMSs based on the surface obtained from point clouds was analyzed in [9.] Three versions of laser scanner, a fringe projection version with structured white light scanner and computer tomography (CT) with X-ray version were analyzed. Three calibrated artefacts and two test parts were used for comparative purpose. Results from calibrated artefacts were used for evaluation of measurement uncertainty. The paper [10] focused on two laser triangulation scanners mounted on a CMM and an Articulated measuring arm. Design of Experiment (DOE) is used to optimize surface parameters in the process of reconstruction of complex parts. An accuracy of generated surface by reverse engineering method depends on the number point from point cloud, number of triangles in polygon model and filtering noise. Comparison of the quality of scanned data at two different 3D scanners, optical and laser is presented in [11]. A comparative study included a dimensional and geometrical inspection of the special design of a test part. The part was produced by additive technology. From dimensional and geometrical evaluation better results have been obtained for laser scanner. Also, smaller deviations of comparison scanned data with CAD model have been achieved for a laser scanner. The paper [12] proposed an approach for determining the accuracy of 3D optical structured white light scanner. The acceptance test based on VDI/VDE 2634-part 3 standard has been applied for the evaluation accuracy of an optical scanner. All the parameters from this standard were successfully evaluated with the aim of evaluating the accuracy of the optical scanner in laboratory conditions. In [13] a review is made of aspects affecting the accuracy of the optical 3D scanner. The aspect of calibration, exposure, number of images, scanning angle and quality of used reference points were examined. Conclusion of this research is that the quality of referent points has greater impact on quality and accuracy of the results. In [14] a procedure for performance testing of CT scanners is presented according to VDI/VDE 2617-13. In this study which includes a probing error test, length measurement error test and resolution test, two CT scanners were analyzed. The authors proposed some solutions that can help in the performance of verification process. Empirical approach to uncertainty analysis of X-ray computed tomography measurements is made in [15]. The research is based on the application of a series of standards ISO 15530 and review of other empirical methods for the estimation of CT measurement uncertainty. Measurement uncertainty approach for corrected measurements results, uncorrected measurement results and uncertainty evaluation based on maximum permissible error (MPE) are presented. The authors in [16] focused their study on comparison of dimensional measurements generated at a CMM with contact probe and an X-ray CT. Complex parts with internal structures and mechanically compliant form for the CMM and X-ray CT were analyzed. Also, a method for estimating uncertainty of CT measurement tasks was assumed. Differences between CMM and CT dimensional measurement of object characteristics in the range of 0.6 mm to 65 mm reached a value of up to 5 µm or less for most of the measurements. Expanded measurement uncertainty calculated for CT measurements ranged from 1 µm to 20 µm.

This paper aims to analyze the accuracy and measurement uncertainty of different CMSs by measuring the reference artefact of flatness (optical flat) of known calibration values. The output from each analyzed CMS is a set of coordinate points (x, y, z) that are analyzed in an independent software analysis. The coordinates of the sampled points will contain all the imperfections of that measuring system and the estimated measurement error will be compared with the calibrated value of the flatness error. In that way, a comparative analysis of the accuracy of different coordinate measuring systems for the measurement task of the error of flatness will be carried out. This study also describes the methodology of estimation measurement uncertainty in the case of form error.

2 MATERIALS AND METHODOLOGY

To test the accuracy and measurement uncertainty of different CMSs, the measurement of the flatness standard - the optical flat was performed. One of the factors of uncertainty when measuring on a CMS is a workpiece due to different types of deviations (form, waviness, roughness) [17, 18]. By using optical flat, the uncertainty caused by the workpiece can be neglected. It should also be noted that in coordinate metrology there is a strong interaction between the measurement strategy (number and position of points) and the deviation of the workpiece from the nominal geometry. In a way, by using flatness standard, the uncertainty factor of this interaction can also be neglected. However, it should be borne in mind that each sampling point does not have the same sampling error caused by CMS hardware and that this may have an impact on measurement error and measurement uncertainty when forming the substitutional geometry (in this case the reference plane).

Figure 1 Workpiece-optical flat

The workpiece is shown in Fig. 1 and its characteristics are given in Tab. 1.

Table 1 Specification of the optical flat

Manufacturer	Mitutoyo
Thickness (L)	12 mm
Diameter (D)	60 mm
Certified error of flatness δ_{cal}	0.03×10^{-3} mm
Uncertainty of calibration	20×10^{-6} mm

The ZygoVerifire MST interferometer was used to obtain the calibration values of the optical flat (Tab. 1) and the calibration procedure was performed at the "Orao" Bijeljina Aviation Institute, Bosna and Hercegovina.

2.1 Coordinate Measuring Systems

Most common way of classification of CMSs is by the type of probe - contact and contactless. Coordinate measuring systems with contact probes are most used because of their high accuracy and lower measurement uncertainty. Typically, examples of contact CMSs include the CMM and the articulated measuring arm with a contact probe. The most popular contact measuring sensors in CMMs are point-to-point sensors. Also, there are scanning measuring sensors that not only detect the deflection (i.e. contact) of the measuring probe but even measure the amount of deflection of the measuring sensor. Since the deflection of the measuring sensor is known, this information can be used as feedback for the CMM. Measuring sensors that use a scan mode are less accurate due to acceleration and variable friction during scanning but can measure more points in less time. Most contactless technology is based on triangulation principle which detects reflected light of external source from the surface of the analyzed object. External sources could be a laser, light beam, or some kind of radiation. Examples of CMS with contactless probe are laser scanner, X-ray computed tomography, laser tracker and technologies with structured light and photogrammetry [8]. The advantages of contactless CMS concerning contact are the measurement of inaccessible parts of the workpiece and the speed of acquisition of data points of the real surface. CMSs with non-contact sensors are expanding in the industry and the manufacturers of these systems are working on the development of these systems in order to bring their metrological characteristics closer to contact CMSs.

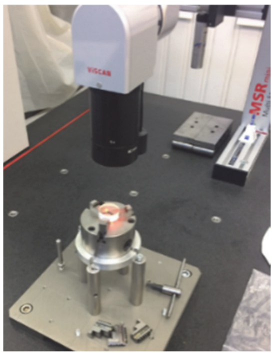
Estimation of parameters of the accuracy of coordinate measuring systems is one of the most common research directions in the field of dimensional metrology. For contact-type CMSs, standard methods for estimating accuracy and measurement uncertainty have been established, while for CT systems the standard procedures for this purpose are still in progress.

It is a well-known fact that measurement accuracy (error) can be defined as a measured value minus a reference value. Since the calibration value of the flatness is known, the accuracy of the measurement for any measurement task can be determined from this statement. It is recommended that measurements be performed several times under different conditions so that the measurement results contain as many systematic and random effects as possible. In this case, the actual value of the measurement is taken as the mean value.

Also, the Guide to the Expression of Uncertainty in Measurement (GUM) can be used for any measurement. In the case of coordinate metrology, it is necessary to know the coordinates of the points that define the error band (minimum and maximum point) and the equation of the reference geometric primitive. It should be noted that commercial software used in different CMSs does not provide information on the equation of the reference geometric primitive and this is another reason to use a non-commercial software solution. In this study, the metrological performance of the following CMSs was analyzed: the coordinate measuring machine, articulated measuring arm with a contact probe, optical scanner and industrial CT. The measurement systems used in this study with the accuracy parameters defined by the manufacturer are shown in Tab. 2. The first coordinate measuring system, CMM Carl Zeiss Contura G2 RDS, has the possibility of contact and non-contact measurement. Also, contact measurement can sample points discretely (point by point) and continuously (scan).

Table 2 Coordinate Measurement Systems

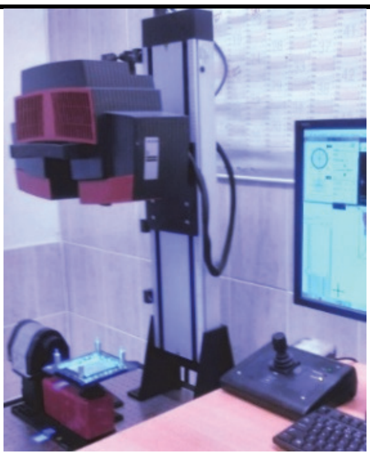
Articulated measuring arm with contact probe
Model: Nikon MCAx 2.0+
Volume length accuracy: ± 33 µm
Point repeatability: 23 µm



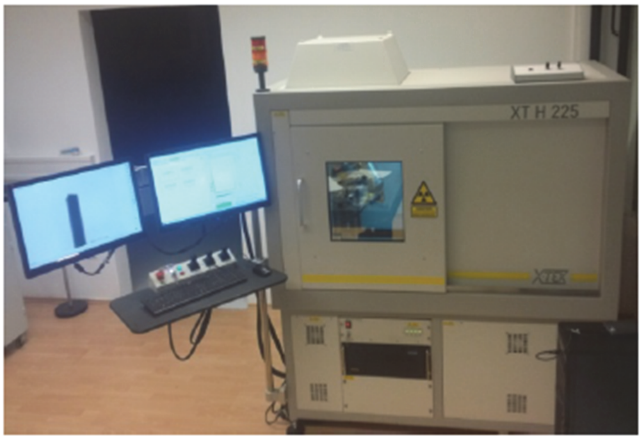
CMM Carl Zeiss
Model: Contura G2 RDS

Contact probe
$MPE_{\mathrm{E}} = (1.8 + L/300)$ µm
$MPE_{\mathrm{P}} = 1.8$ µm
$MPE_{\mathrm{THP}} = 3.5$ µm

Optical sensor
$MPE_{\mathrm{E}} = (10 + L/350)$ µm



Optical scanner
Model: ATOS II Triple Scan
Accuracy: 30 µm



Industrial CT
Model: Nikon X TH 225
Accuracy: /

2.2 Estimation of Flatness Error

Tolerance of flatness is often present in the technical documentation to meet the functional requirements of the product. In recent times, conventional measuring instruments for verification of flatness have almost never been used and the use of CMSs is dominant. The real surface is described (digitized) with a finite number of points that are sampled with the CMS sensor and then the reference (substitutive) plane and the points furthest from this plane are determined in the software. The ISO standard recommends that the minimum zone (MZ) method be used to estimate the flatness error [19]. Bundle of plains through the one-point method is a non-commercial verified software used to estimate the flatness error over a set of sampled points from all considered CMSs. The principle of operation of this method is described in [20, 21]. It should be noted that over 20 MZ -based flatness error estimation methodologies have been developed so far and some of them have been implemented in the CMS software. It was found that there are generally more or fewer differences between the errors of flatness estimated with different methodologies. Thus, by applying single software for all CMSs, software impact (point coordinate processing) is excluded as one of the factors influencing accuracy and measurement uncertainty.

2.3 Estimation of Measurement Uncertainty According to GUM

The general opinion of experts in the field of coordinate metrology is that the GUM approach is very limited and that many assumptions must be introduced. One of the assumptions is that all sampled points within the CMM working space have the same uncertainty, which is incorrect. However, in some cases, and if there are no other available methods, they can give satisfactory results [22, 23]. It should also be noted that the GUM approach is very economical and relatively simple. The GUM approach consists of the following steps: defining the measurement process (model) and input uncertainty sources, estimating standard uncertainties of input uncertainty sources, propagating uncertainty through the model, and determining extended uncertainty. Accordingly, the first step is to determine the equation of the reference plane by the minimum zone method (Eq. (1)), then determine the flatness error of the equation δ as the sum of the distances between the point at maximum (x_1, y_1, z_1) and minimum distance (x_2, y_2, z_2) from the reference plane, Eq. (2). Eq. (2) represents the model equation.

$$z = c + ax + by \tag{1}$$

$$\delta = \frac{(z_1 - z_2) - a(x_1 - x_2) - b(y_1 - y_2)}{\sqrt{1 + a^2 + b^2}} \tag{2}$$

Estimation of the combined measurement uncertainty of the flatness error requires the determination of standard uncertainties and the propagation coefficients of each element in Eq. (2). The combined standard uncertainty is determined by Eq. (3).

$$\begin{aligned} u_\delta^2 = {} & \left(\frac{\partial \delta}{\partial x_1} u_{x_1} \right)^2 + \left(\frac{\partial \delta}{\partial x_2} u_{y_1} \right) + \left(\frac{\partial \delta}{\partial y_1} u_{z_1} \right) + \\ & + \left(\frac{\partial \delta}{\partial y_1} u_{x_2} \right) + \left(\frac{\partial \delta}{\partial z_1} u_{y_2} \right) + \left(\frac{\partial \delta}{\partial z_2} u_{z_2} \right) + \\ & + \left(\frac{\partial \delta}{\partial a} u_a \right) + \left(\frac{\partial \delta}{\partial b} u_b \right) + 2 \frac{\partial \delta}{\partial a} \frac{\partial \delta}{\partial b} \rho_{ab} \mathrm{u}_{\mathrm{ab}} . \end{aligned} \tag{3}$$

Standard uncertainties denoted by u_{xi}, u_{yi}, u_{zi}, represent the uncertainty of the sampled point and are dominated by geometric errors of CMS and sampling system errors in the first place, as well as the impact of environmental conditions on the CMS and the measurement process. The standard uncertainties u_a, u_b, $u_a u_b$ and ρ_{ab} represent the uncertainty of the applied algorithm for obtaining the reference plane. The coefficients that determine the orientation of the reference plane, a and b, are correlated and ρ_{ab} represents the correlation coefficient.

3 RESULTS OF THE COMPARISON

The coordinates of the sampled points from different CMSs were imported into non-commercial software in .txt format. The digitized flat surface of each CMS contained 50 coordinates of points randomly distributed across the surface. When measuring CMM by scanning and contactless mode, point filtering and outlier removal were not performed because Calypso software was not used and the non-commercial software solution does not have this capability. Since the measurement on the same CMS was performed several times, a flatness error was determined for each measurement, then the mean value was calculated. The following parameters were used for CT measurements: 110 kV X-ray source voltage, 240 µA X-ray source current, pixel size 127 µm and X-ray pre-filtering with 0.1 mm thick copper filter.

Table 3 The equations of reference plane and flatness error values of corresponding CMSs

Code	Type of CMS	Equation of reference plane	Flatness error $\bar{\delta}$in mm
I	CMM Zeiss Contura G2 VAST XXT-point by point mode	$z = 0.75026 + 0.0000226x - 0.000051y$	0.00031
II	CMM Zeiss Contura G2 VAST XXT-scanning mode	$z = 0.751324 + 0.0000494x - 0.0000636y$	0.00063
III	CMM Zeiss Contura G2 VAST XXT-optical sensor ViScan	$z = -0.000299 + 0.0000421x - 0.0000254y$	0.00077
IV	Optical scanner Atos II Triple Scan	$z = -0.0019554 + 0.0000935x + 0.0000533y$	0.00643
V	Articulated measuring arm Nikon MCAx 2.0+ with contact probe	$z = 0.0002557 + 0.0001612x - 0.00001014y$	0.02594
VI	X-ray CT Nikon X TH 225	$z = -0.0051485 + 0.002213x + 0.00762y$	0.04079

Tab. 3 shows the equations of the reference planes for one sampling at different CMSs and the mean values of the flatness error. Fig. 2 shows the position of the reference planes obtained by applying the MZ method of the sampled point from different CMSs whose equations are given in Tab. 3. It can be seen in Fig. 2 that the reference planes obtained from the points sampled by the CMM contact method (point by point and scanning mode) were shifted relative to the other reference planes. This fact is not so important and is a consequence of the coordinate system from which the points are expressed. More important is the fact that the planes are not parallel to each other, which indicates the difference in the geometric errors of the observed CMS.

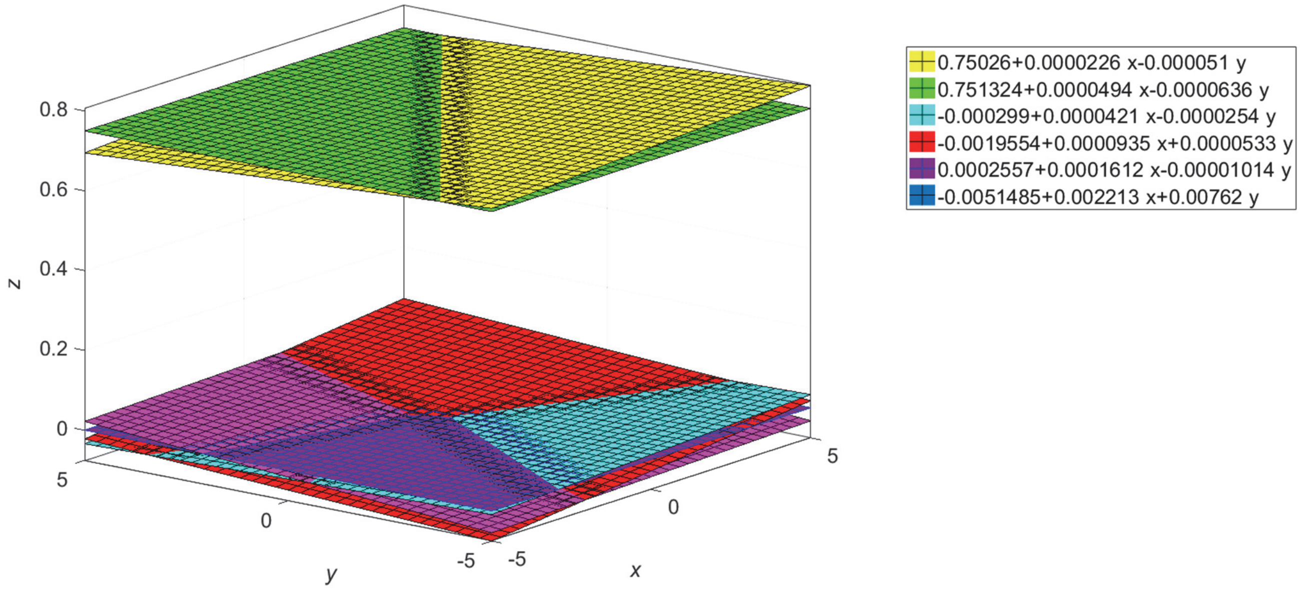


Figure 2 Position of reference planes in 3D space

3.1 Estimation of Systematic Error

The accuracy of a particular CMS, i.e. systematic error b is determined according to Eq. (4):

$$b = \left| \bar{\delta} - \delta_{\text{cal}} \right| \tag{4}$$

Based on Eq. (4), systematic errors were obtained for each analyzed CMS and the results are presented in Tab. 4 and Fig. 3.

Table 4 The values of systematic error of CMSs

Type of CMS	Systematic error of CMS b / mm
I	0.00028
II	0.00062
III	0.00074
IV	0.00641
V	0.02591
VI	0.04076

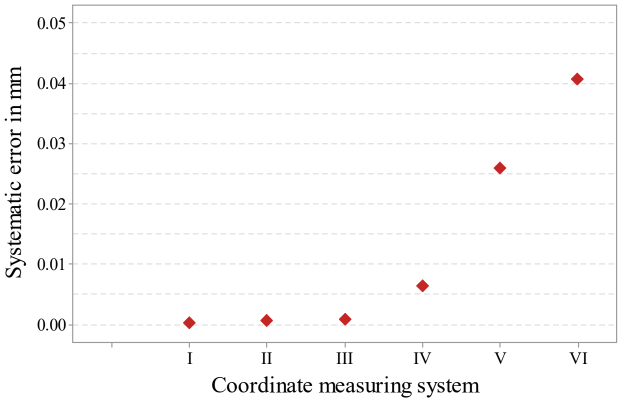


Figure 3 Graphical representation of systematic errors

Compared to other measurement systems, a CMM is characterized by high accuracy regardless of the way of sampling mode. It can be concluded that the measurement error is more influenced by the geometric errors of the CMM than the probe errors. The Atos optical scanner proved very good performance and its results are close to the results obtained on the CMM. The articulated measuring arm has significantly worse results compared to the above-mentioned measuring systems. However, the systematic error is within the specified accuracy of the measurement system. CT is the system with the least accuracy. The CT as a measuring system in industry can provide a meshing of object made from different materials and low thickness but its accuracy is much lower compared to other analyzed systems. A high value of dimensional errors is mainly the result of the selection of the minimum gray scale parameter which separates the contour of an object from noise.

3.2 Estimation of Measurement Uncertainty

The measurement uncertainty is calculated from Eq. (3). The first six terms in the equation represent the uncertainty of the min-max sampled points. Simplification has been introduced and one-sixth of the specification's maximum permissible error or accuracy is taken as the uncertainty of the point, depending on the CMS under consideration. Recommendations for determining individual parameters in Eq. (3) can be found in [24]. The standard uncertainties of the other three terms in Eq. (3) are determined based on repeated measurements and obtaining multiple MZ reference planes. Extended uncertainty U is obtained by multiplying the combined measurement uncertainty u_δ and the coverage factor k = 2. Expanded uncertainty values of flatness error for different CMSs are presented in Tab. 5.

Since the manufacturer did not define the accuracy parameter for CT, in that case it is not possible to estimate the uncertainty of the flatness error.

Table 5 The extended uncertainty of corresponding CMSs

Type of CMS	Extended uncertainty U / μm
I	0.85
II	1.65
III	4.7
IV	14.14
V	15.6
VI	/

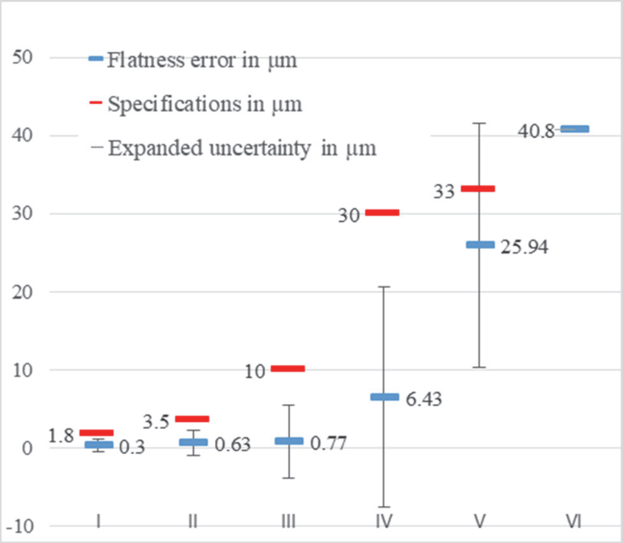


Figure 4 Comparison of results

Fig. 4 presents the total measurement result (measurement error ± extended measurement uncertainty) in relation to the specification limits of a particular CMS.

4 CONSLUSION

Verification of metrological characteristics is among basic activities in the process of assessing the accuracy and achieving traceability of measurements using CMSs. There are different types of digitization techniques with different degrees of accuracy and for different areas of application. This research is based on the evaluation of four CMSs with different metrological characteristics and different operating principles. The aim of this paper is to provide information about possible deviations occurring during sampling points at calibrated surfaces with defined shape errors. Based on the results of the research and their comparison, it can be concluded that the geometric accuracy of CMS has the greatest influence on the flatness error and the associated uncertainty. Also, the difference in results is implied by the use of different measurement probe. However, it could be observed that some types of non-contact probe do not give very small beams compared to the contact probe. The results of this research make a significant contribution to the application of CMSs in the industry. This contribution is reflected in the quality of sampling points and limitations in the application of coordinate systems with tactile and contactless sensors and the possibility of their application for the purpose of dimensional and geometric inspection of products.

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