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EFFICIENT PROCEDURE FOR FREEFORM SURFACE ACCURACY ASSESSMENT

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Abstract

The document provides a procedure for accuracy assessment of freeform surfaces based on CMM sampling limited to critical areas, *i.e.* areas of distribution of the highest deviations predicted from a theoretical or experimental CAD model of deviations. The value of the form deviation is determined by the point furthest away from the nominal CAD model, *i.e.* the critical point. Critical areas on the deviation model are determined taking into account the uncertainty of predicting a high of an actual surface profile at a critical point. All steps of the procedure are performed in the CAD environment. The proposed procedure is more efficient than the traditional method of distributing points over the entire surface with the same measurement uncertainty. The procedure is demonstrated by assessing the accuracy of a component after three-axis milling, using a theoretical model of the deviations.

Keywords: freeform surface, accuracy assessment, CAD model of deviations, critical area, coordinate measurement.

1. Introduction

Objects with freeform surfaces are being increasingly designed for functional and aesthetic reasons. CAD/CAM techniques and numerically controlled machines are used to design, manufacture and inspect the accuracy of such surfaces. Multi-axis milling centres are commonly used for machining, while *numerically controlled coordinate measuring machines* (NC CMMs) with touch probes are commonly used for accuracy assessment. The result of a measurement is a set of measurement points with a specified distribution on the surface to be measured. For each measurement point, the value of the local deviation is determined, *i.e.* the distance of the point from the CAD model of the nominal surface in the normal direction. The purpose of surface accuracy assessment is to verify that the observed deviations are within the tolerance zone. A form deviation is determined as the doubled highest absolute value from the obtained set of local deviations [1]. Thus, the goal of the measurement is to determine the maximum deviation from the CAD model, that is, to find the critical point on the measured surface.

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To inspect the accuracy of freeform surfaces, the initial step is to map the actual geometry to a cloud of points. This is typically done using *coordinate measuring machines* (CMMs) with ball-tip probes [2]. Numerically controlled CMMs enable the automatic generation of probe movement paths, allowing for the creation of nominal points on the CAD model based on specified criteria. The distribution and number of these points is called the sampling strategy. The complete measurement plan also includes the configuration of the probe set, *i.e.* the orientation and length of the stylus and the diameter of the ball tip. The sampling strategy for point-by-point inspection could be roughly divided into blind sampling and adaptive sampling [3].

Freeform surface measurements are usually taken on a regular $u - v$ grid of points using the *UV* Scanning option built in the CMM software. This blind sampling method does not require knowledge of the nominal geometry or features to be measured. However, it produces a large number of unnecessary points and prolongs the measurement time. An efficient measurement is one that maximizes the probability of identifying the greatest deviation, *i.e.* the *critical point* (CP) while minimizing the number of measurement points needed to achieve the required level of measurement uncertainty. Researchers have presented different approaches to solving this problem, using adaptive control of the number and distribution of the sampling points – some pay more attention to the number of points, others to how they are distributed. The distribution of points should depend on the geometry of the surface, the type of geometric feature to be diagnosed, the tolerance or the requirements for further processing and analysis of the measurement data. Adaptive sampling can be categorized into two classes, *i.e.* geometry-based strategies and production-based strategies [3].

Geometry-based strategies distribute the sampling points according to some specified geometric features, *e.g.* the curvature, the patch size, and the arc length [4–7]. Researchers point out that regions with greater curvature are predicted to have the highest deviations [7, 8]. Geometry-based strategies are more efficient than blind sampling strategies, but have some drawbacks – they are intuitive and do not provide the ability to control the number of points according to tolerances [3]. Another way of searching for critical points is to use adaptive strategies based on a machining error model to predict critical areas and to rationally distribute measurement points in these areas [9–12]. In [9], the points are iteratively sampled from a form error model (substitute geometry), which is constructed by superimposing appropriate form errors on the nominal data to represent the manufactured surface. In [10], a scanning line distribution strategy is proposed to adaptively distribute the scanning lines using the star-shaped mode; adaptive mesh is first built according to the model which describes the relative value of the probability to generate a larger form error. In [11], the distribution of machining errors is predicted by analysing the geometric feature of the surface and the dynamic property of the machine tool. In [12] a strategy is proposed that takes into account the characteristic marks left by machining processes, this method can be used in serial or mass production. When applying such methods, AI support is invaluable in collecting and analysing data from the manufacturing process to determine a 3D model of the deviations (i.e. a 3D model of the actual object) [13].

The sampling strategies described in the literature require a lot of knowledge, skilled personnel and most of them are not feasible in an industrial environment due to the high density of measurement points and therefore measurement time, they also require the use of additional expensive software. Most methods do not take machining influences into account. These include: uniform point distributions in Cartesian and parametric space, distributions based on the size of surface patches/segments of the profile. On the other hand, methods based on profile length or curvature take little account of machining effects. The difficulties of integrating the developed algorithms with typical CMM software are noted by the authors themselves. No method has yet been developed for efficiently assessing the accuracy of freeform surfaces that is simple and applicable in an industrial setting, that can be used in a CAD environment, and that can be easily implemented in the CMM software.

The measured surface is assumed to be accurately represented by the measurement points. However, it is important to note that measurement results are always subject to uncertainty. One of the sources of this uncertainty is the sampling strategy, which is dependent on the operator's decision. An irrational measurement plan can be the source of the dominant uncertainty component. The amount of information available about the surface to be measured depends on the measurement parameters used. The reason for this is that the measurement parameters, tip diameter and sampling step, cause a loss of information about surface irregularities due to geometric-mechanical filtration of the irregularities [14–17].

This paper proposes a universal procedure for efficient accuracy assessment of freeform surfaces. The procedure is based on CMM sampling, which is limited to *critical areas* (CAs). These areas are defined as regions where the highest deviations are predicted by a theoretical or experimental CAD *deviation model* (DM). If a theoretical DM is used, it is possible to construct CAs in the CAD system during the product design stage. This approach makes it possible to apply the procedure in assessing the accuracy of unit-produced parts, such as injection mould components. For serial production, CAs can be determined based on an experimental DM designed using measurement data. The proposed procedure for accuracy assessment is significantly more efficient than the commonly used approach of distributing of points according to regular grids across the surface. The measurement uncertainty is the same in both cases, as it is dependent on the measurement parameters.

The procedure was successfully used to assess the accuracy of various freeform surfaces with different curvatures. This work presents the procedure's course when CAs were determined from a theoretical DM after milling. After selecting the optimal measurement parameters, the determined theoretical DM was verified by measuring the entire surface according to a regular grid of points. The obtained measurement data were then used for experimental verification of the new procedure.

2. Approach description

Considering the tolerance given in the geometric specification, measurements must be planned to meet the measurement uncertainty. The choice of measurement parameters – tip diameter and sampling step – is crucial. Recommendations given in the literature can be used here [16]. The purpose of the measurement is to locate the CP of an *actual surface* (AS), which is the point furthest from the nominal surface. In general, this can be a point below the nominal CAD model (Min. deviation) or a point above the model (Max. deviation).

The basic element of the procedure is the DM, which can be a theoretical or experimental model. All procedure steps are performed in a CAD environment, and commonly available engineering software can be used here. The DM is superimposed on the nominal CAD model to obtain the *actual surface model* (ASM). This model is used to plan a strategy for sampling the surface to find its CP. Sampling takes place in CAs, the size of which depends on the uncertainty in predicting the height of the AS profile at the CP.

In determining the form deviation the values of the local Min. and local Max. deviations are important, not their location. Therefore, in the uncertainty study, the variability of profile heights $H = |\text{Max.} - \text{Min.}|$ is investigated.

2.1. Flow of the procedure

To determine CAs on the ASM, it is necessary to calculate the uncertainty of the estimating H of the measured surface relative to the H of ASM. This uncertainty consists of uncertainties due to the effects of three factors: an AS mapping by DM/ASM, manufacturing/machining process and measurement process (Section 2.2). It is assumed that the H of the AS is within the determined uncertainty limit. Assuming that the CP of the measured surface falls within the uncertainty layer with respect to the CP of the ASM, the next step is to construct an offset surface relative to the nominal CAD model at a distance U from the CP. This surface defines the limit of the uncertainty layer over the measured surface. The curves of the intersection of these two elements define the boundaries of the CAs on an ASM. These boundary curves are then projected onto a nominal CAD model to be implemented in the NC CMM software, and measurement points are then generated according to a regular grid of points within these boundaries (Section 2.3). The local deviation observed in the CP of the measured surface determines the value of the form deviation and thus the result of the accuracy assessment. A flowchart of the process is shown in Fig. 1.

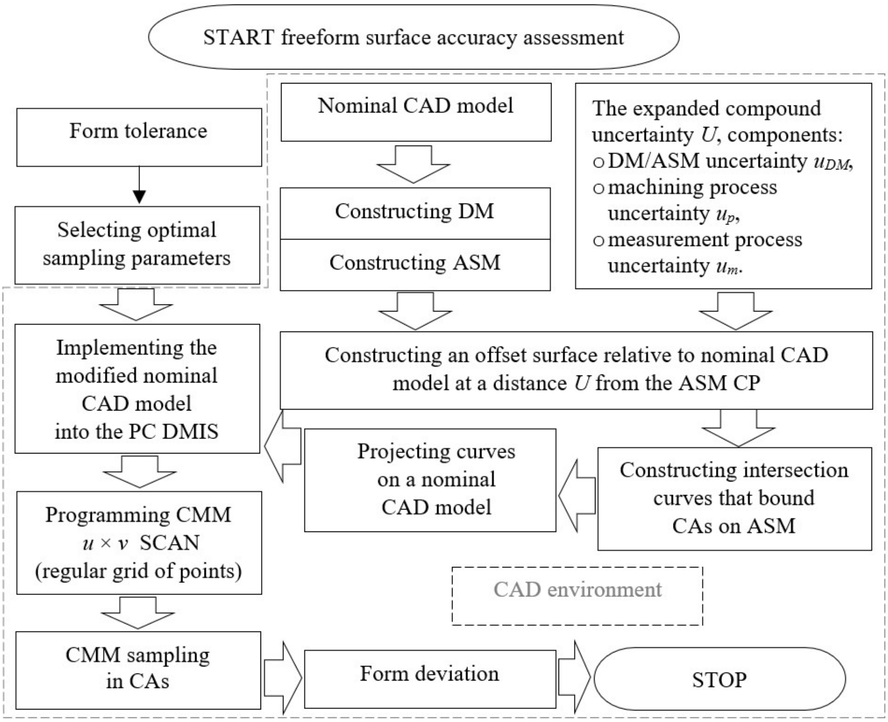

Fig. 1. Flowchart of the new procedure.

2.2. Way of calculating the uncertainty in predicting the H of the AS profile

The procedure for constructing CAs involves the effects of three processes: modelling DM (ASM), machining, and measurement, each with an uncertainty that makes up the compound standard uncertainty u. H-variability should be examined in these processes. If we denote the standard uncertainty component of ASM determination as u_{ASM}, the machining/producing process uncertainty as u_p, and the measurement uncertainty as u_p, then the compound standard uncertainty u of the estimating H of the AS relative to the H of ASM:

$$u = \sqrt{(u_{\mathrm{ASM}})^2 + \left(u_p\right)^2 + (u_m)^2}, \tag{1}$$

- the u_{ASM} is determined from variability studies of DMs/ASMs, by comparing the *Hs* of DMs of many surfaces of different shapes with the *Hs* obtained from measurements; such data are available during the verification of the adequacy of deviation models, taking into account both the values of local deviations and their distribution;
- u_p is determined from variability tests of the machining process for the *Hs* of many surfaces of the same nominal shape machined/produced by this process;
- u_m is the measurement uncertainty including the effect of sampling parameters.

The data needed to determine uncertainty is readily available in modern Industry 4.0, where manufacturing processes are subject to multi-criteria monitoring supported by AI.

2.3. Method for constructing CAs

The construction of the CAs in which the sampling is to be implemented is realized in the CAD system, where the nominal CAD model, the DM, and the knowledge of the expanded uncertainty U in the estimation of the H of the AS value are required. According to the flowchart in Fig. 1, modelling steps in CAD software proceeds as follows:

- construct the ASM by superimposing the DM on the nominal CAD model;
- construct an offset surface from the nominal model at a distance U from the ASM (the intersection curves of these elements are the constraints of the CA boundaries on the ASM);
- project the CA boundaries/intersection curves onto the nominal CAD model;
- implement the modified CAD model into the CMM software and generate measurement points within the CAs.

The method for constructing CAs relative to the CP (Max.) of ASM is shown in Fig. 2.

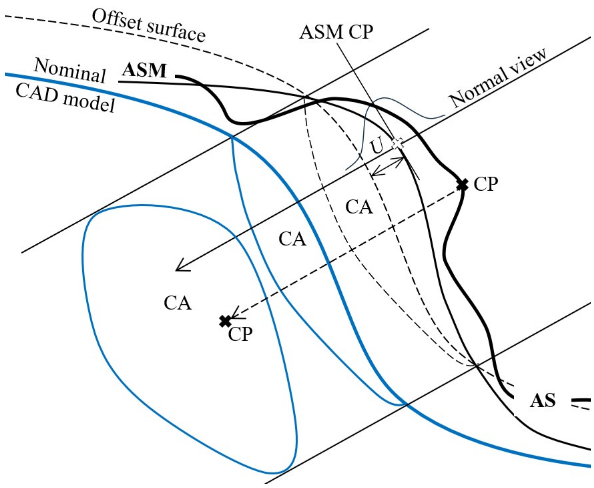

Fig. 2. Method for constructing CAs relative to the CP of ASM.

The number of critical areas depends on the complexity of the surface to be measured – the greater the variation in curvature, the greater the number of areas for the specified measurement uncertainty (which depends on the design requirements). For the same surface and lower accuracy requirements (*i.e.* higher required measurement uncertainty), the number of critical areas may increase, and certainly the sampling area (number of points) will be greater.

3. Experimental research

According to the procedure described in Section 3.1, the form accuracy of freeform surface element of a steel (WCLW) specimen with dimensions (50 × 50) was assessed Fig. 3. The form tolerance of the surfaces of these dimensions in accuracy class IT12 is $t = 0.03$ mm.

The artefact was obtained in the three-axis milling process using a ball-end mill of 6 mm in diameter with the rotational speed equal to 8000 rev/min, the working feed of 800 mm/min and the zig-zag cutting path in the XY plane ($Ra = 1.51$ µm).

The measurements were carried out on a Global Performance CMM (PC DMIS software, $\mathrm{MPE}_E = 1.5 + L/333$) equipped with a Renishaw SP25 probe and a 20 mm stylus with a ball tip $d = 2$ mm in diameter. A sampling step of $s = 1$ mm was adopted (see Section 3.2).

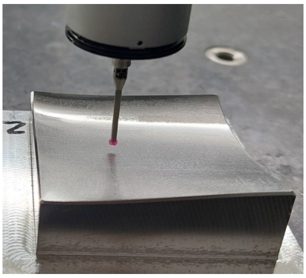

Fig. 3. View of the measured specimen.

3.1. Constructing and verifying the DM

The new method for efficient accuracy assessment is demonstrated using an example where a theoretical DM after three-axis milling was used to determine CAs. In three-axis milling, the main source of surface deviations is tool deflection. Based on literature data [18, 19] and own work, a mathematical model of deviations was determined and the local deviations of the model at the measurement points were calculated. In the calculations, the values of the machining parameters used in the machining process and the parameters characterizing the mechanical properties of the tool and the machined material were assumed. The text file was then implemented in CAD software to construct the DM. The map of the DM is shown in Fig. 4. The model was verified experimentally based on the results of sampling the entire surface of the workpiece using a typical procedure built into the DMIS PC software, SCAN $u \times v$ according to a regular grid of points. The distribution of measurement points is shown in Fig. 5. As a result of the measurement, 2500 local deviations were obtained, the map of which is shown in Fig. 6. A comparison of the modelling and measurement results is given in Table 1.

Table 1. The DM verification, summary of modelling and measurement results, 2500 measurement points.

	DM [mm]	**Observed deviations** [mm]
Min.	0.0012	-0.0003
Max.	0.0407	0.0411
H	0.0395	0.0414
Mean	0.0174	0.0149
Std. deviation	0.0062	0.0074

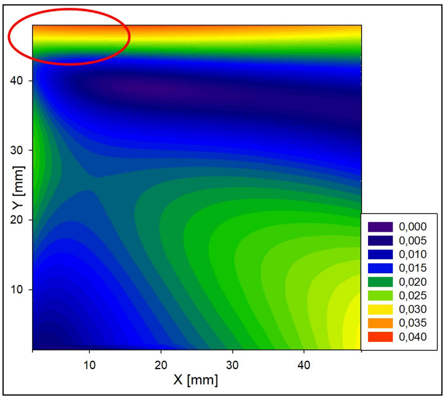

Fig. 4. Map of the DM, three-axis milling, the area of the highest deviations is pointed out.

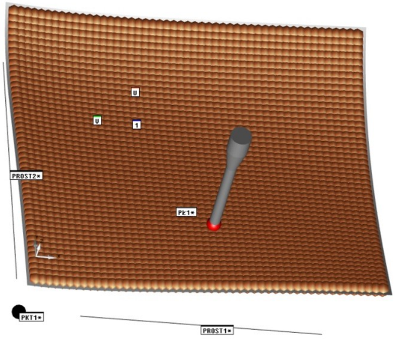

Fig. 5. Measurement points distribution. Measurements according to the procedure built into the PC DMIS, regular grid of points, *Scan* $u \times v$, (1 × 1) mm, 2500 measurement points.

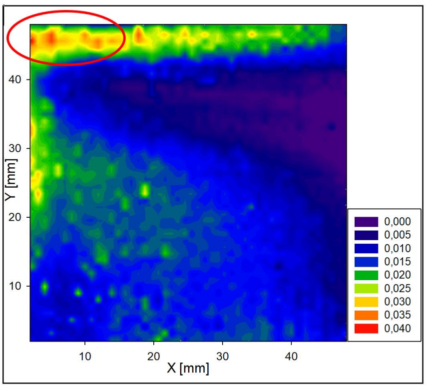

Fig. 6. Map of observed local deviations (2500 measurement points).

As can be observed (Fig. 4, Fig. 5, Table 1), the experimental verification of the constructed DM is positive, both as to the value of the deviations and their distribution. The deviations caused by the deflection of the cutter have positive values so that the local deviation in the CP has a positive value.

3.2. Calculation of the uncertainty of the H in the CP of AS prediction

The loss of information about the real surface due to geometric-mechanical filtration of irregularities causes inherent mapping errors that affect the measurement uncertainty. Based on our own research results published in [14], for a form tolerance of $t = 0.03$ mm, the adopted measurement parameters were $d = 2$ mm and $s = 1$ mm, the expanded measurement uncertainty was 2.6 µm. All measurements in the presented experiment were performed with the same parameters. Other components of the uncertainty were determined according to Section 2.2.

- $u_{\mathrm{DM/ASM}}$ – theoretical models of 6 specimens milled on two machine tools were experimentally verified by comparison with the results of full surface sampling on the CMM using the same sampling parameters. Statistical parameters – arithmetic mean and standard deviation – were determined for the differences in the *Hs* of the observed and theoretical profiles (Table 2).
- u_p – the variability *Hs* of eight surfaces of the same nominal shape machined under the same conditions was considered (Table 2).
- u_m was determined on the basis of *Hs* in eight repetitions of the entire surface sampling, additionally, the uncertainty associated with the loss of information about the irregularities of the surface for the adopted sampling parameters (0.0013 mm) was also taken into account.
- The results of the measurements and calculations are presented in Table 2.

Table 2. Summary of data used in the uncertainty calculations.

<table>
<tr><td colspan="2" rowspan="2"></td><th colspan="6">*H* [mm]</th><th>Std. deviations [mm]</th><th>Std. uncertainties [mm]</th></tr>
<tr><td colspan="2">Observed</td><td colspan="2">DM</td><td colspan="2">Difference</td><td rowspan="7">0.0089</td><td>$u_{\mathrm{DM/ASM}}$</td></tr>
<tr><td rowspan="6"></td><td>1</td><td colspan="2">0.0378</td><td colspan="2">0.0521</td><td colspan="2">–0.0143</td><td rowspan="6">0.0036</td></tr>
<tr><td>2</td><td colspan="2">0.0411</td><td colspan="2">0.0469</td><td colspan="2">–0.0059</td></tr>
<tr><td>3</td><td colspan="2">0.0414</td><td colspan="2">0.0395</td><td colspan="2">0.0019</td></tr>
<tr><td>4</td><td colspan="2">0.0425</td><td colspan="2">0.0312</td><td colspan="2">0.0115</td></tr>
<tr><td>5</td><td colspan="2">0.0541</td><td colspan="2">0.0488</td><td colspan="2">0.0051</td></tr>
<tr><td>6</td><td colspan="2">0.0510</td><td colspan="2">0.0443</td><td colspan="2">0.0070</td></tr>
<tr><th colspan="8">Machining process *Hs* variability</th><td></td><td>u_p</td></tr>
<tr><td>0.0506</td><td>0.0637</td><td>0.0546</td><td>0.0664</td><td>0.0517</td><td>0.0484</td><td>0.0507</td><td>0.0469</td><td>0.0067</td><td>0.0027</td></tr>
<tr><th colspan="8">Measurement process *Hs* variability</th><td></td><td>u_m</td></tr>
<tr><td>0.0408</td><td>0.0397</td><td>0.0359</td><td>0.0394</td><td>0.0341</td><td>0.0366</td><td>0.0363</td><td>0.0399</td><td>0.0024</td><td>0.0015</td></tr>
<tr><td colspan="8">Compound standard uncertainty of the H in CP prediction</td><td></td><td>0.0047</td></tr>
<tr><th colspan="8">Expanded uncertainty, expansion factor 2.5</th><td></td><td>0.0120</td></tr>
</table>

The expanded compound uncertainty of H in CP prediction u is the key criterion for the CA constructing. Based on a number of tests, an uncertainty of $u = 0.012$ mm can be recommended for assessing the accuracy of milled surfaces for processes carried out on machines meeting the requirements of the standards.

3.3. Constructing CAs

The method described in Section 2.3 was used. A text file containing the results of the calculation of local deviations caused by cutter deflection was imported into the CAD system software. Next, CA modelling operations were performed according to the flowchart in Fig. 1 and the method shown in Fig. 2. The local deviation in CP has a positive sign, as shown in Fig. 4. The modelling effect is presented in Fig. 7. Surface sampling was then carried out in the constructed CAs.

Fig. 7. CAs on a nominal CAD model in RHINO software.

3.4. Measurements according to the developed sampling plan

The nominal CAD model prepared as described in Sections 2.3 and 3.3 was implemented in the CMM PC DMIS software, and then the SCAN UV option built into the software was used to distribute points according to a regular grid of (1 × 1) mm. Figure 8 shows the distribution of points in the CAs in the PC DMIS software. With the same uncertainty as measuring at 2500 points, a CP was located by sampling the surface at 427 measurement points. The results of the measurements are shown in Table 3.

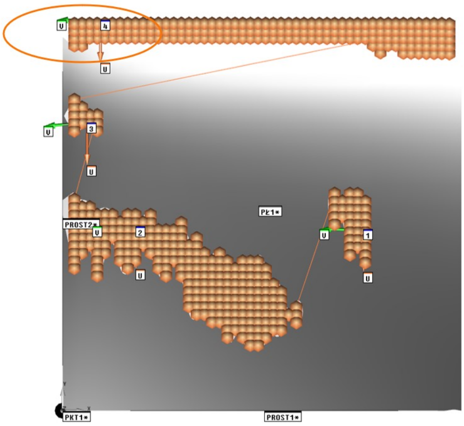

Fig. 8. Distribution of measurement points in the CAs, PC DMIS software, 427 points.

Table 3. Comparison of measurement results.

Measurement parameters		**Number of measurement points**	**Grid points size**	**Max.**	**Form deviation**
d [mm]	s [mm]		[mm]	[mm]	[mm]
2	1	2500	1 × 1	0.0411	0.0822
2	1	427	1 × 1	0.0424	0.0848

The results (Table 3) show that the measurement result for the new method is insignificantly different (within the uncertainty limit) from that of the traditional method, and the measurement efficiency of the new method for this sample is six times higher. Less important here is the observation that the accuracy of the measured surface has not been positively verified.

4. Conclusions

The article presents a new procedure for proceeding in the assessment of the accuracy of freeform surfaces. Based on the experience with this procedure, supported by the presented results, practical conclusions can be drawn.

- The proposed procedure for assessing the accuracy of freeform surfaces provides high surface measurement efficiency while ensuring optimal measurement uncertainty; in the completed studies, the efficiency was 6-9 times higher than with the traditional method of sampling the entire surface.
- From the metrological point of view, the measurement results of the new method are equivalent to those of the method in which the entire surface is scanned.
- The procedure can be used to assess the accuracy of freeform surfaces produced by various methods, the availability of theoretical or experimental (positively verified) surface deviations model is required.
- The statistical data needed to calculate the uncertainty for critical point location prediction is usually known to machine tools and measuring machines operators or can be easily determined from the results of previous measurements.
- CAs can be constructed in commonly available and used engineering software.
- The more stable the processing conditions, the smaller the variation of the manufacturing process and the smaller the area of the CAs, and thus the greater the efficiency of the measurement.
- The efficiency of the method can be increased for machining/production in AI-controlled processes, according to the concept of Industry 4.0.
- If the CMM meets the requirements for accuracy and measurement range and the complexity of the object allows it to be measured on the CMM, and the CMM software includes CAD modules, no limitations were identified in the use of the proposed method.

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