PERFORMANCE ASSESSMENT OF GEOMETRY MEASUREMENTS WITH MICRO-CT USING A DISMOUNTABLE WORK-PIECE-NEAR REFERENCE STANDARD

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Abstract

Analyzing the dimensional measurement performance of industrial computed tomography (CT) systems [1] requires reference standards. Current reference standards feature simple (regular) geometries to assess standardized machine characteristics and to compare CT system performance. But these standards do not allow a performance analysis for real work piece measurements. For this reason, a novel work-piece-near designed part with new and unique properties is used here. The general principles and features of this dismountable reference standard - also for the analysis of the non-destructive testing performance of CT - are presented in [2]. In this paper we describe the analysis of the dimensional measurement performance of a sample micro-CT system using the new reference standard. The analysis also covers the performance for the measurement of sculptured (freeform) surfaces and of interior geometries. Reference measurements have been conducted applying a dedicated tactile coordinate measuring procedure ensuring a safe and correct assessment of the sculptured surface. The paper describes this new work flow and discusses the properties of the measurements. The authors presume that dismountable work-piece-near reference standards can be used as sensitive verification and analysis tools for checking the entire measurement process of industrial CT measurements for a given product.

1. Introduction

Computed tomography (CT) has been in use as an industrial non-destructive testing technique for several decades while its application as a coordinate measuring technique came into use roughly 10 years ago [1]. Nowadays, industrial CT systems dedicated to dimensional measurements are designated to be full coordinate measuring machines (CMMs). Certain systems now feature CT as one sensor of a multi-sensor CMM.

The performance of CMMs has been classically analyzed by the aid of dedicated reference standards (e.g. performance testing according to DIN EN ISO 10360, VDI/VDE 2617, ASME B89.4). These reference standards feature simple regular geometries (planes, cylinders or spheres). The main objective of these bodies is to assess the characteristics of the system under study. Thus, the performance and the measurement uncertainty of real work piece measurements can hardly be determined with these reference standards and the knowledge of the assessed characteristics. The procedures to test CT systems are similar to CMM tests. VDI/VDE 2630-1.3 draft guideline describes the use of reference standards based on regular geometries for dimensional CT systems. However, CT systems today are used only occasionally for measurements of regular geometries. More often, CT measurements are performed at sculptured (freeform) surfaces. Additionally, the influence of the work piece material, of the part geometry and the assessment strategy are usually quite strong for the case of CT. Thus, the significance of characteristics for real work piece measurements is less than for classical CMMs featuring tactile and optical sensors. Consequently, there is a strong need to have reference standards which are dedicated to a certain measurement and work piece application. These reference standards are desired to be as similar as possible to the real work piece. Fur-

thermore, the reference standards are required to be calibrated by independent measurement techniques.
You would think that the use of a sample work piece as a reference standard (master part) could help. Unfortunately interior geometries usually can not be calibrated without destroying the part. Also, a segmented (cut) part usually does not offer a solution as correlations between the single segments are lost.
A new approach to solve this problem is presented in [2]. A highly artificial but nevertheless work-piece-near designed part is used here. The general features of this reference standard and its application in the field of non-destructive testing with CT are presented in [2]. In this paper we describe the application of this reference standard (Figs. 1-4) to analyze the dimensional (geometry) measurement performance of CT systems utilized for the measurement of cast parts of the given size. The presented concept can be transferred to other work pieces.

2. The dismountable reference standard

The reference standard [2] (Figs. 1-4), a cast part (miniaturized single cylinder head, size 12 cm x 9 cm x 6 cm, "Mini-Cylinder-Head No. 5") made of aluminium by ACTech GmbH, Freiberg/Saxony, Germany, features several unique properties; it is work-piece-near designed, it is dismountable and finally its segments can be registered by means of regular geometries. This body features as a work-piece-near body sculptured surfaces. These object regions contain non-trivial dimensional measurement tasks for the CT systems under study. The body consists of four segmented (cut) pieces (Figs. 2-4), whose measurement data can be registered mathematically (by using CAD software) by means of inserted and carved out reference elements. These reference elements are spheres and inner and outer cylinders. Certain nearly planar faces have been flattened by milling to enable an easier mounting and serve as reference planes for the tactile CMM measurement. For standard CT applications, the three spheres of each segment are used to align the data sets. The spheres (mounted on carbon fibre rods) of a 3 mm diameter are located in areas of the part where they are protected by the surrounding material but can be measured by tactile CMM. The geometry of the cuts has been chosen to assess the interior of the part by tactile CMM while keeping the number of segments as low as possible. Despite being modified, the general geometry of the body and also the X-ray absorption properties remain near to the original cast part. The surface of the standard features domains of different roughness ranging from Rz = 2 µm (Ra = 0.2 µm) (milled surfaces, EDM machined and ground surfaces) to Rz = 134 µm (Ra = 27µm) (sand cast inner and outer regions; outer sand cast regions have been refractory dressed).

Fig. 1: The raw body of the new work-piece-near reference standard; state before segmentation and modification (block size 12 cm x 9 cm x 6 cm)

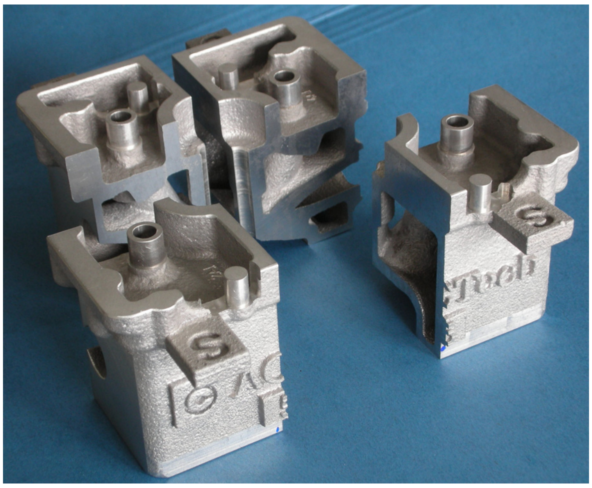

Fig. 2: The new work-piece-near reference standard; state after segmentation into four segments by EDM and milling of inner/outer cylinders on top plane

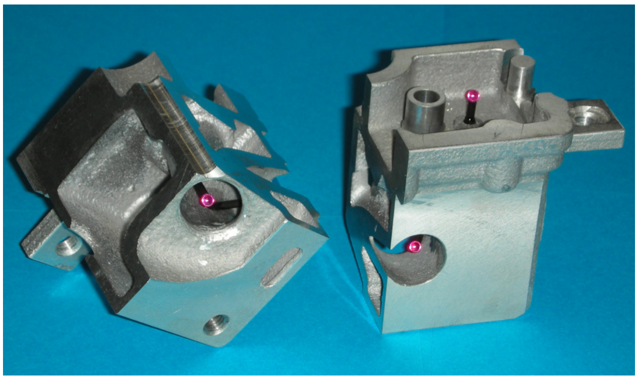

Fig. 3: Two of the four segments of the new work-piece-near reference standard; state after mounting of reference ruby spheres on carbon fibre rods (three spheres for each of the four segments)

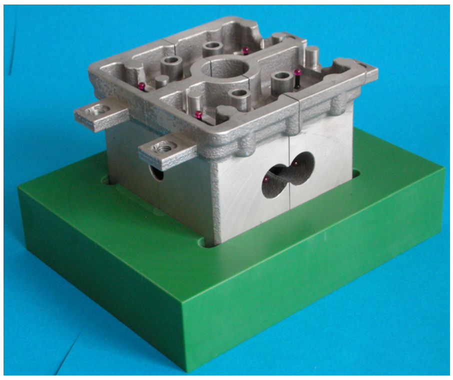

Fig. 4: Mounting of the four segments of the work-piece-near reference standard on holding plate (observe the four ruby spheres visible on the top plane of the reference standard)

The authors presume that dismountable work-piece-near reference standards can be used as sensitive verification tools for checking the entire measurement process of industrial CT measurements for a given product. In contrast to the use of artificial reference standards, e.g. ball bars, gage blocks or step cylinders, the native and complete measurement process of the product can be monitored. The use of reference standards of this type will result in better process control and a more secure process chain.

3. Traceability of CT measurements

The traceability of a measurement to the relevant SI unit(s) is achieved by a statement of the measurement uncertainty. For CT measurements, certain methods for the assessment of the measurement uncertainty can be applied [3]. The GUM approach for the set-up of an uncertainty budget is not applicable for CT because of the complex nature of the whole measurement process. Due to the fact that complete and validated simulations of the whole CT measurement process and especially for the measurement of sculptured surfaces have not existed up to now or are present only on an early stage [4], empirical studies of the measurement uncertainty are currently the only feasible way. The empirical analysis of the measurement uncertainty requires the ability to assess the measurement errors of the measurement system. Typical studies [5, 6] analyze the measurement errors of CT by viewing the outer geometry of the part or by opening the part in a heavily destructive way to assess the inner geometries. Especially continued case studies of the performance for inner measurements are impossible due to the destruction or distortion of the part and the loss of reference coordinate systems. The dismountable reference standard enables the analysis of measurement errors in the interior by means of a comparison to tactile-assessed data. Alternatively, CT data sets of the individual segments, measured with a higher resolution and in different orientations, can serve as reference (Fig. 5). Systematic effects from the assembly and the modification of the reference standard can be measured by the comparison of the unmodified and the segmented reference standard in common regions.

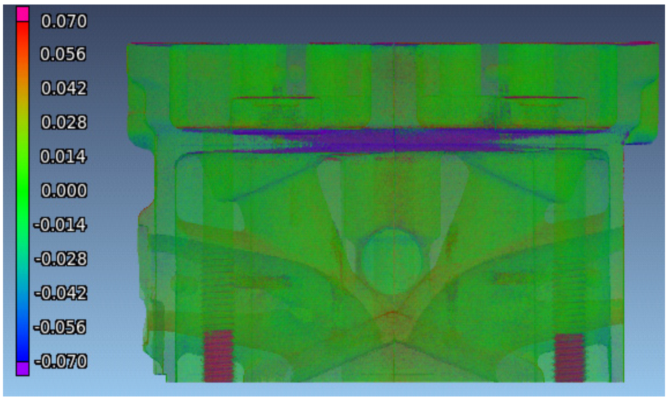

Fig. 5: Sample data of the new dismountable reference standard. The deviation of a common CT measurement (one data set) of the 4 assembled segments and 4 CT measurements of the 4 single segments is shown. The 5 measurement data sets have been registered by the use of the 3 respective spheres of each segment. Positive deviations larger than 0.07 mm on the base are caused by cover bolts and negative deviations below -0.07 mm on the upper part are caused by the reduced signal-to-noise ratio due to the long horizontal material plane (present in assembled state)

4. Enhanced reference standard calibration and application work flow

4.1 Motivation and selected approach

Reference measurements for determining the geometry of reference standards must be traceable to the SI unit of length – the meter. Optical CMM measurements feature many complex and often unknown sources of uncertainty (e.g. surface influence). Thus, CMM measurements with tactile probing are still favourable for making traceable reference measurements. But also for tactile measurements, the realization of traceability is a challenge, especially for the measurements of sculptured surfaces. Tactile CMM measurements of any surface must be performed with the correct probing vector (cf. Figs. 6, 7 taken from Zeiss Calypso manual). While for regular geometries, the correct probing is ensured by the applied knowledge about the geometry to be probed, the case for sculptured surfaces is different. Quite often probing is performed on the basis of nominal information (e.g. from CAD draft). An incorrectly estimated surface normal results in an oblique instead of a normal probing and causes a wrong probe radius correction. The situation is quite unsatisfactory as – on the basis of the CAD-given information – it is not clear which measured points are strongly distorted. It can only be assumed that especially areas of the geometry with significant (nominal) curvature tend to be more critical than more planar areas.
An optimized approach is to assess the present surface normal by an appropriate measurement. One measurement strategy to assess the normal direction at a surface point of interest can be an iterative measurement of a tripod of (three) points around the estimated location of the point of interest. The positions of the tripod points form a plane whose normal vector can be an estimate of the present surface normal at the point to be measured. This strategy will be tested and explained in the next section.

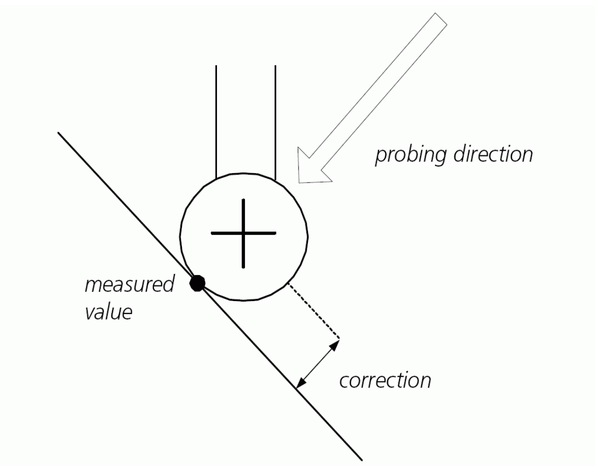

Fig. 6: Probing direction and probe radius correction (simple scheme)

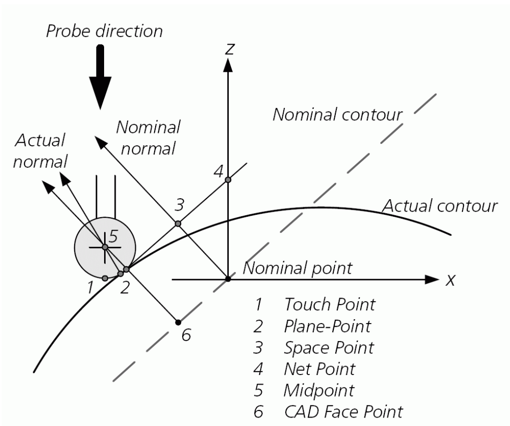

Fig. 7: Probing direction and probe radius correction in the presence of nominal surface information. Point 2 ("Plane-point") is the most probable contact point for the tactile probing of the surface

For any analysis of CT measurement performance, a comparison of the CT measurement and the reference measurement has to be performed in the proper way. Usually this comparison (actual-nominal value comparison) is performed in such a way that the CT measurement of data type surface is set as reference (nominal value) and the reference measurement of the data type point is set as actual. This wrong procedure is applied for two reasons. First of all standard CMM measurements assess only the coordinates of the measured point and not its (required) surface normal! Secondly, nearly all standard software packages for performing actual-nominal value comparisons (so-called inspection modules) do not perform the required correct comparison direction. A further problem with this procedure is that in many cases the reference points are not assessed in the proper way. Measurements are often performed on the basis of nominal (CAD) information (see section above). The correct procedure would be to project the reference point along its attributed normal direction towards the CT measured surface under analysis. The length of this projection yields the numerical value of the correct comparison.

4.2 Measurement application sequence

The measurement and analysis sequence covers the steps: pre-processing, tactile CMM measurement, CT data processing and post-processing (analysis). The sequence of steps is described in the following.

Pre-processing (preparation for tactile CMM measurement):

- Reference CT-measurement (result: voxel data set)
- Scaling correction of voxel data set(s) with the 3 distances between the 3 spheres of each segment
- Definition of coordinate system in voxel space (Volume Graphics VGStudio Max 2.05) using regular geometry elements (planes) of the body
- Surface extraction using adaptive threshold in the specified coordinate system with moderate simplification (VGStudio Max 2.05) (result: STL data set)
- Definition of measurement points and extraction of point coordinates and point normals (Geomagic Studio 11) (result: 6D data set with point coordinates and point normal directions)

As a reference CT measurement (here for segment No. 1), a measurement of good quality without strong artefacts (visible errors in voxel data set) has been chosen. The simplification during the surface extraction serves for better handling due to a smaller STL surface data set and yields, as a low pass filter, a better estimate for the starting surface normal vectors, as small surface distortions are flattened.

Tactile CMM measurement (of segment No. 1):

- Definition of coordinate system from real part features (planes) with CMM (Zeiss Calypso 4.10)
- Measurement of the three spheres of the segment in the previously defined coordinate system (Zeiss Calypso 4.10)
- Measurement of a sub-set of the point cloud with “Space Point Mode” probing method (of Zeiss Calypso 4.10) and “Plane-Point” evaluation for the probing radius correction (Fig. 7)
- Threefold iteration of the probing scheme taking the normal vector of the previous iteration as the respective starting value
- Repetition of measurement cycle (including the iteration) with tripod radius 1 mm, 0.5 mm and 0.2 mm (result coordinates and normal vectors of 35 points)

Tactile measurements have been performed using a Carl Zeiss CMM (type Prismo 7 S-ACC) with a specified maximum permissible error for length measurements MPE_E of 0.9 µm + $2.9 \cdot 10^{-6} \cdot L$ (with measured length L) and a 2 mm diameter probe. The probing has been programmed using Zeiss Calypso 4.10 software. Certain modules for the processing and manipulation of large point clouds (in the order of 5000 points) as independent point objects and the use of point-like data with attributed normals have been built. Due to the fundamental character of the study, a sub-set of 35 points taken from a point cloud of 5018 points has been measured at different regions of the sculptured surface (see sample view, Fig. 8). From the 35 points, 27 points are located on cast regions (sculptured surfaces), 7 points are located on milled planar surfaces and one point lays on an EDM machined and ground planar face. In total 9 points of 35 origin - in assembled state of the reference standard - from internal geometries.

The iterative probing scheme shows a good convergence of normal directions and assessed coordinates. For nearly all points, already the first iteration results in a significant enhancement. The case for point 732 is different (of point cloud with 5018 points, Fig. 9). Even after 4 iterations the results differ in the order of 0.3 mm whereas values in the order 2 µm to 15 µm are achieved for all other points (for the optimum tripod radius 0.5 mm). It can be further seen from the iteration, that for some points (1 point of 35) the tripod radius 1 mm tends to be too large while for 4 points of 35, the tripod radius of 0.2 mm is shown possibly to be too small. This can be seen from the range of values of the coordinates in the probing direction (Figs. 10, 11, 12) where “Range 3-4” indicates the change between the last two measurements of the iteration process. Observe the behaviour of point 732 of the full point cloud indicated as point 10 in Figs. 10, 11 and 12.

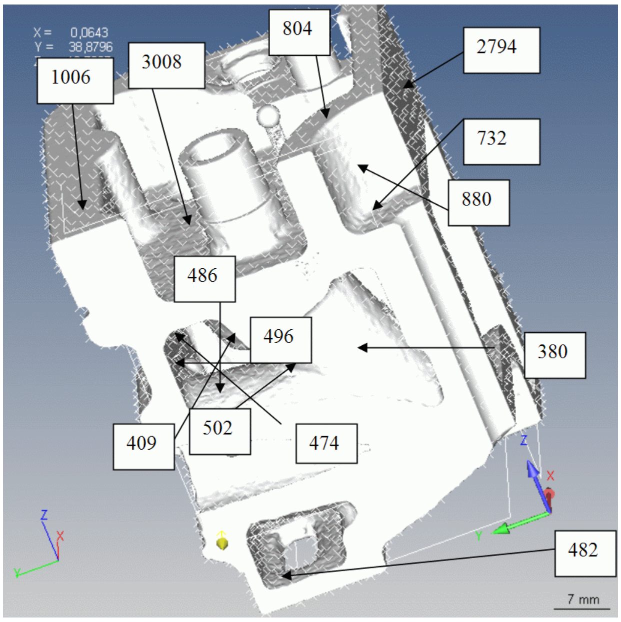

Fig. 8: Sample view of the point measurement strategy of segment No. 1. White crosses indicate locations of the original point cloud with 5018 elements

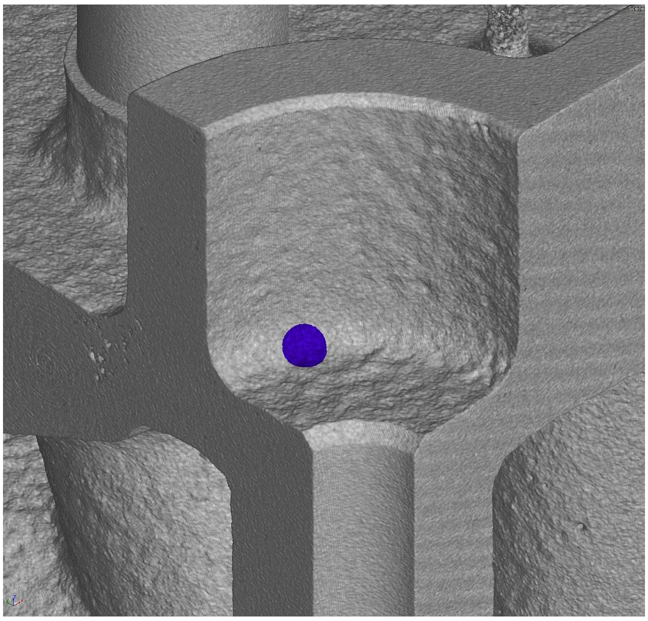

Fig. 9: View of area around point 732. Observe the distinct surface roughness and high curvature at this point (blue: ROI patch with 2 mm diameter)

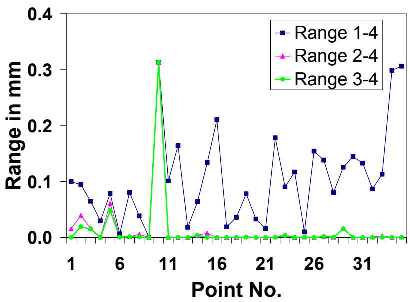

Fig. 10: Range of iterations 1-4, 2-4, 3-4 with a tripod radius of 1 mm

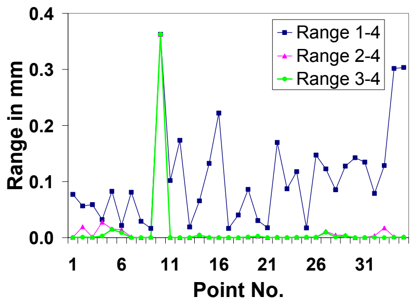

Fig. 11: Range of iterations 1-4, 2-4, 3-4 with a tripod radius of 0.5 mm

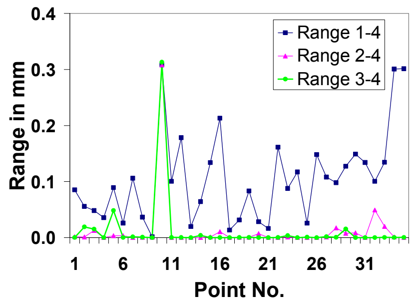

Fig. 12: Range of iterations 1-4, 2-4, 3-4 with a tripod radius of 0.2 mm

A further effect to be observed is the lateral shift of the assessed probing points during the iteration. The convergence of the iterations is clearly visible also for the lateral shifts, but not as fast as normal to the surface (see Figs. 10-12 for this). The total lateral shifts amount to 35 µm on average for tripod radius 1 mm and 25 µm on average for tripod radius 0.5 mm and 0.2 mm. Again point 732 shows peculiar behaviour. Its lateral shift is to be observed in the order of 0.15 mm.
The measurement uncertainties of the CMM measurements have been assessed using the Virtual CMM simulation method. Single point measurement uncertainties ($k = 2$) of the order of 1 µm – 19 µm have been observed. These numbers do not yet include the full influence of the surface roughness. Usual uncertainty approximations attribute an additional uncertainty contribution in the order of $Rz/2$ to the measurement. For many cases, this statement gives an upper limit to the ob-

served effect. For the measurements performed here, only effects of less than *Rz*/4 can be estimated, but this needs to be verified further.
The study of the new probing scheme was successfully accomplished. Nearly all measured points showed very satisfactory behaviour during the iterative probing process. Measurement points with problematic probing could be detected from the iterative probing scheme. For these points either an extended iteration could be performed or the attributed measurement uncertainty would have to be enlarged. The developed tools and methods will allow for CMM measurements of several thousand points. Thus, an entire and complete assessment of the geometry of sculptured surfaces with an enhanced quality is possible.
In the present form, the tripod of points is chosen to be static for each iteration. In further studies these three points will be chosen with an arbitrary angle around the estimated normal vector. One drawback of the applied measurement strategy in this study is, that it does not give precise results at critical points, e.g. saddle points. Thus, the probing strategy has to be further enhanced [7].

<u>CT data processing:</u>

- Scaling correction of voxel data set(s) with the 3 distances between the 3 spheres of each segment or average of these values for the assembled state
- Registration of voxel data set(s) with the 3 attached ruby spheres of each segment along the coordinates of these spheres as measured by CMM (rotation and shift of voxel data set)
- Definition of spheres at CMM measured position (sphere radius 1 mm) within voxel data set(s)
- Creation of regions of interest (ROI) from defined spheres (Fig. 13)
- Surface extraction within spherical ROIs of the voxel data set(s) without simplification (result: independent surface patches in STL format building one STL object net) (Fig. 14)

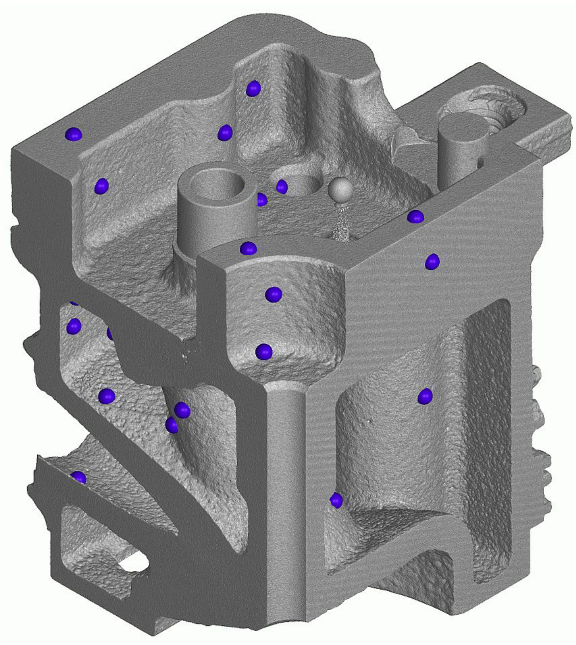

Fig. 13: Sample CT voxel data set of segment No. 1 with visualization of 35 spherical regions of interest (ROI) around tactile-assessed measurement points

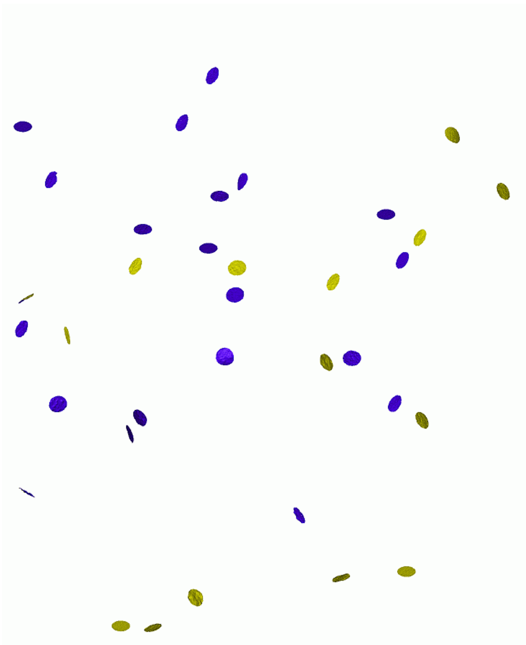

Fig. 14: Extracted surface patches within previously defined ROIs (see Fig. 13) for sample CT data set

The registration of the CT voxel data sets along the tactile measurement has been chosen as this allows a full automatization of the process for different CT measurements using a predefined template. The approach of defining regions of interest around the tactile measured point coordinates enables a much faster processing of the surface extraction and decreases the size of the STL models for each CT measurement analysis drastically. Thus, a faster and easier analysis of results within inspection software becomes possible. The radius of the spherical regions of interest (here 1 mm) is chosen to be large enough to recognize effects of curvature and roughness.

Post-processing (final analysis):

- Actual-nominal value comparison taking the CT measurement as reference (nominal value) and the CMM measurement (point data) as actual (GOM ATOS 6.2) [old scheme]
- Actual-nominal value comparison taking the CT measurement as actual and the CMM measurement (point and normal data) as reference (nominal value) (GOM ATOS 6.2) [new scheme]

Due to the previous registration of CT measured and tactile CMM measured data sets no registration for the final analysis within the inspection software GOM ATOS has been performed.

5. Experimental results – Analysis of measurement errors of sample micro-CTsystem

The dismountable reference standard is applied to assess the measurement errors of a sample micro-CT system of BAM for CT measurements of a sculptured surface geometry. The CT system features cone beam geometry and Feldkamp reconstruction. Thus, the dismountable reference standard is measured in different orientations; 3 measurements of segment No. 1 alone and 3 measurements of the assembled state of all 4 segments (Tab. 1). The analysis of the assembled state is performed for segment No. 1.

Data No.	State	Voltage in kV	Filtering	Voxel size	Voxel volume size
3442a	Assembled state (4 segments) (see Fig. 4)	205	0.5 mm Cu 0.75 mm Ag	$(69.8\ \mu m)^3$	2029 x 2029 x 1813
3497a	Assembled state (4 segments) (see Fig. 4)	210	0.5 mm Cu 0.75 mm Ag	$(69.8\ \mu m)^3$	2029 x 2029 x 1813
3498a	Segment 1 alone	210	0.5 mm Cu 0.75 mm Ag	$(48.0\ \mu m)^3$	2029 x 2029 x 1715
3499a	Segment 1 alone, first oblique setting	210	0.5 mm Cu 0.75 mm Ag	$(48.0\ \mu m)^3$	2029 x 2029 x 1715
3500a	Segment 1 alone, second oblique setting	210	0.5 mm Cu 0.75 mm Ag	$(48.0\ \mu m)^3$	2029 x 2029 x 1715
3510a	Assembled state (4 segments) oblique setting	210	0.5 mm Cu 0.75 mm Ag	$(104.6\ \mu m)^3$	1251 x 1001 x 901

Tab. 1: CT measurement parameter

The tactile CMM data indicate the distinct influence of the surface roughness on the CMM measurement. Even magnified visualizations of the CT measured surfaces processed with an adaptive threshold method from the voxel data do not reveal the true roughness profile of the surface. This can be seen from the measurement data at point 732 (see Fig. 9). Tactile probing with the 2 mm probe shows significant residuals (in the order of 0.3 mm) as the iteration does not converge.
A further point to note are the systematic residual errors of all CT measurements. In total 8 different CT measurements have been analyzed from two independent CT systems (including the 6 measurements mentioned in Tab. 1). All these measurements feature a measurement geometry independ-

ent residual error of the same size. Respective positions of the three reference spheres of the segment No. 1 are shifted. The average errors reach 35 µm, 21 µm and 12 µm for the 3 spheres, respectively. The origin of these errors is to be further investigated.
The design of the dismountable reference standard and the underlying design principles can be optimized by attaching 4 reference spheres to each segment. Thus, the redundancy of lengths (6 lengths instead of 3) allows for better monitoring of systematic deviations and for better process control.

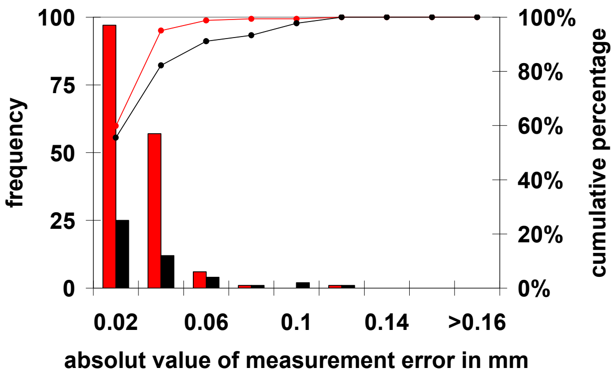

Fig. 15: Histogram of measurement errors for all 35 analyzed points cumulated for all 6 CT measurements (black: points on machined faces, red: points on sculptured surface). Presentation for wrong (but standard) comparison sequence (tactile CMM measurement set as actual and CT measurement set as reference (nominal value))

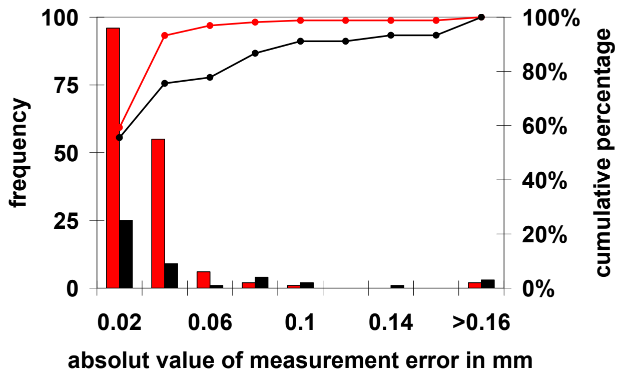

Fig. 16: Histogram of measurement errors for all 35 analyzed points cumulated for all 6 CT measurements (black: points on machined faces, red: points on sculptured surface). Presentation for correct comparison sequence (tactile CMM measurement set as reference (nominal value) and CT measurement set as actual)

The actual-nominal value comparison of tactile CMM measurement and CT data has been performed twice. The wrong comparison direction, where the CT measurements is set as reference (nominal value) and the tactile CMM measurements are set as actual shows a distribution of errors with high values of the order of 0.1 mm (Fig. 15). The correct comparison direction, where the tactile CMM measurement is set as reference (nominal value) and the CT data is set as actual shows a similar distribution but includes strong outliers with errors reaching the order of 0.3 mm (Fig. 16)! These strong deviations occur for the CT measurements *3442a* and *3497a* for the assembled state (high penetrated thickness!) at faces which surface normals are parallel to the rotary table axis. The effect has been observed for 4 points in both data sets. Here, a decreased signal to noise ratio of the extracted surface can be expected. Thus, single STL polygons can change their orientation. This causes significant angles the order of 30° between the average surface normal and the local STL facets. The correct comparison direction reveals the real deviations and yields a realistic image of the quality of the CT measurement.
The differences between the machined surfaced (black indications in Figs. 15 and 16) and the cast surfaces (red indications in Figs. 15 and 16)) need to be further analyzed. For the statistics of only 8 points on machined surfaces the result is dominated by the low sample size. The study will be continued with a more dense tactile assessment of the reference body.

6. Summary and outlook

The paper explained the application of a new dismountable reference standard for the analysis of the dimensional measurement performance of industrial CT. Studies have been performed for a sample micro-CT system of BAM. The new reference standard has been measured in different settings and assemblies. The results give valid estimate of the performance of the CT system under study for the dimensional measurement of work pieces of the same type. The analysis also covers internal geometries and sculptured surfaces. Reference standards following the described principles can be powerful tools for analyzing the real performance of CT systems for dimensional measure-

ment tasks in contrast to the more academic numbers given by characteristics (*MPE* values). An outcome of the present study is, that the design of dismountable reference standards can be optimized by attaching at least four reference spheres to each segment instead of the minimum number of three. The additional sphere offers a redundancy of information which ensures a robust and fault tolerant data analysis.
The authors presume that dismountable work-piece-near reference bodies can be used as sensitive verification tools for checking the entire measurement process of industrial CT measurements for a given product. In addition to the use of artificial reference standards, e.g. ball bars, gage blocks or step cylinders, the native and complete measurement process of the product can be monitored. The use of reference standards of this type will result in better process control and a more secure process chain for industrial CT measurements.
The developed CMM probing procedure for the assessment of the geometry of the reference standard has been successfully tested and implemented. It allows for a safer and more reliable assessment of the geometry of sculptured surfaces. The developed probing scheme will be enhanced further. This is the topic of future work.

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