

# Experimental evaluation of the uncertainty associated with the result of feature-of-size measurements through computed tomography

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**Abstract.** Computed tomography for dimensional metrology has been introduced in quality control loop for about a decade. Due to the complex measurement-error cause system, generally no consistent measurement uncertainty reporting has been made. The ISO 15530-3 experimental approach, which makes use of calibrated parts, has been tested for estimating the uncertainty of CT-based measurements of features of size of a test object made of POM. Particular attention is given to the design of experiment and to the measurement uncertainty components. The most significant experimental findings are outlined and discussed in this paper.

## 1. Introduction

Computed tomography (CT) for industrial coordinate metrology has been part of dimensional quality control loop for about a decade. In general, complex-shaped parts with hundreds (even thousands) of features (hidden features as well) can be holistically inspected with great operational advantages over other existing coordinate metrology technologies, such as tactile and/or optical coordinate measuring machines.

CT measurement principle relies on the attenuation of X-rays when propagating through the test object, which depends on the object material and radiographic thickness. For a large number of beam directions, the intensity distribution of the remaining radiation is measured and digitally stored as a grey-value image. The resulting projections of the full object rotation are mathematically processed to create the 3D voxel matrix. Further processing steps over the voxel data allow performing dimensional measurements.

The CT principle and the metrological CT scanner setup give rise to influence factors that affect the performance of dimensional evaluations. They are related to the source (e.g. photon energy, focal spot size), to the detector (e.g. sensitivity, pixel size, exposure time, averaging), to the object (e.g. material, shape, size), to the CT kinematics (e.g. magnification axis and turntable repeatability and accuracy), and mathematical data processing (e.g. segmentation, measuring strategy) [1].

Due to that intricate measurement-error cause system, establishing traceable measurements with CT has been pointed as a key metrology issue. This paper outlines and discusses the use of calibrated workpieces, as specified in part 3 of ISO 15530, for estimating the task-specific uncertainty associated

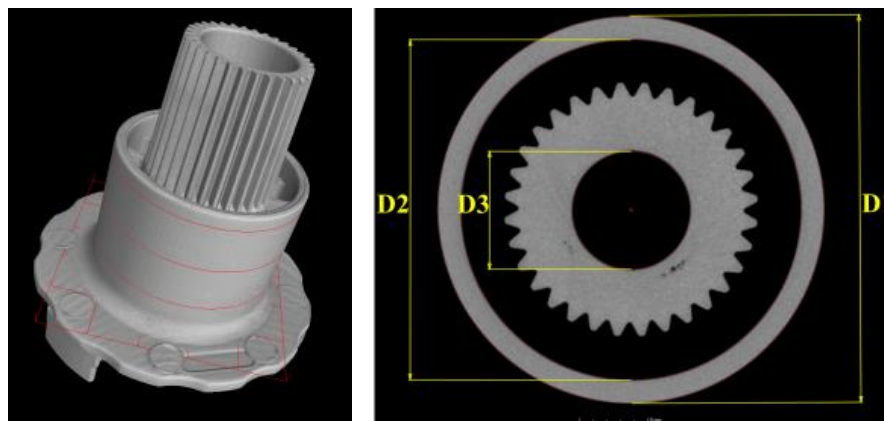


with feature-of-size measurement results. Section 2 shows the intrinsic characteristics of the test object under analysis. Section 3 summarizes the reference and CT measurements of the test object. Sections 4 and 5 present respectively the uncertainty assessment and the most relevant findings.

## 2. Case description

### 2.1. Test object intrinsic characteristics

The industrial part selected for this experimental uncertainty evaluation composes the drive system of a window lift mechanism, and is made of acetal photopolymer (POM). Three intrinsic characteristics were defined in accordance with the technical drawing of the test object: the diameter of the external circumferential line at surface mid-height,  $D_1$ ; the diameter of the internal circumferential line at surface mid-height,  $D_2$  and  $D_3$ . Figure 1 illustrates the test object and the intrinsic characteristics just described.



**Figure 1.** Illustrative image of the test object and the intrinsic characteristics (features of size).

### 2.2. Uncertainty evaluation background

In order to evaluate the uncertainty associated with CT measurements of the intrinsic characteristics, three uncertainty contributions were considered, which are represented by the following standard uncertainties: uncertainty of the parameter of the calibrated test object,  $u_{cal}$ ; uncertainty associated with the measurement procedure,  $u_p$ ; uncertainty associated with the systematic error,  $u_b$ . The expanded measurement uncertainty is obtained by combining the individual standard uncertainties in a root-sum-of-squares manner and multiplying by the coverage factor,  $k$ . Please refer to ISO 15330-3 for more details.

## 3. Measurement setup

### 3.1. Tactile reference measurements

The intrinsic characteristics of the test object were calibrated on a Carl Zeiss PRISMO ultra CMM, which is housed in a temperature-controlled room maintained at  $(20.0 \pm 0.3)^\circ\text{C}$ . All diameters were realized by associating ideal features of type circle to the sampled points (using least-squares method). Measurement uncertainties were estimated using the Virtual CMM software output as well as expert judgment. Table 1 lists the calibration results.

### 3.2. CT measurements

The test object was measured on a Carl Zeiss METROTOM 1500 CT system, which is equipped with a 225 kV micro-focus tube and a  $2048^2$  pixels flat panel detector. The CT system is installed in a temperature-controlled room maintained at  $(20 \pm 1)^\circ\text{C}$ . The CT system manufacturer specifies a MPE for length measurements of  $(9 + L/50) \mu\text{m}$ , using a test piece consisting of 27 ruby spheres mounted

on carbon fiber shafts, and then determining the sphere-center to sphere-center distances of several pairs of spheres [2]; which on the other hand is nearly insensitive to material influence [3].

**Table 1.** Calibration results for the object intrinsic characteristics (best estimates and expanded uncertainties in millimeters).

Feature	Calibration results
$D_1$	$28.211 \pm 0.002$ ( $k = 2$ )
$D_2$	$24.784 \pm 0.002$ ( $k = 2$ )
$D_3$	$8.612 \pm 0.002$ ( $k = 2$ )

To scan the test object, the magnification axis was positioned to project the object using the maximum possible area of the detector (and thus reducing the resulting voxel size). The source voltage was set high enough to avoid beam extinction, and the detector integration time (and sensitivity) set to a convenient value. The source current was then tuned to enhance image contrast and brightness. The number of angular poses was selected as approximately the number of pixel covered by the resulting shadow of the test object in the projection. See table 2.

**Table 2.** Simplified list of the CT control parameters chosen for measuring the test object under analysis.

Parameter	Unit	Value
Source voltage	kV	110
Source current	$\mu\text{A}$	450
Focal spot size	$\mu\text{m}$	50
Integration time	s	1
Detector binning	--	2x2
Magnification	--	7.53
Voxel size	$\mu\text{m}$	53
No. of projections	--	800

In fact, the selected CT settings agree with some lessons learnt for reliable dimensional analysis of feature of size [4]: (a) the focal spot size should be closer or smaller than the voxel size; (b) the detector gain setting would not affect average size, albeit increasing the gain would result in noisier images; (c) the smaller the angular increment, the lesser the image background noise; (d) the higher the image resolution, the lesser the image background noise; (e) the higher the magnification factor, the lower the measured biases.

Regarding the surface definition from the voxel dataset, the standard ‘iso-50%’ threshold value was applied globally. From the material boundary thus defined, 3600 points evenly spaced around the circumferential line were extracted for each intrinsic characteristic, and the ideal feature of the type circle associated to the points using the least-squares fitting method.

#### 4. Uncertainty evaluation

Measurements performed on the CT system were entirely repeated three times, and for each intrinsic characteristic, the mean value of the measurement result and the standard uncertainty associated with measurement procedure were determined. The test object temperature inside the CT system enclosure was measured in order to properly compensate the temperature effects and to estimate the standard uncertainty associated with the systematic error.

Table 3 shows the resulting individual standard uncertainties, expanded uncertainty and bias (after temperature correction) for each feature of size of the test object. Since the dominant factors were the calibration uncertainty and procedural uncertainty, which were nearly identical for all characteristics, the expanded uncertainty after correcting the bias would be virtually the same,  $U_1 = 0.003$  mm.

From table 3 other inferences could be drawn, such as the dominant role played by the bias in CT measurement performance; bias eight times higher than the expanded uncertainty for characteristic  $D_3$ . Treating the empirically determined bias like other uncertainty component,  $U_2$  [5], a ratio  $|b| / U_2$  can be calculated, which shows that bias accounts for about 50% of the expanded uncertainty.

##### 4.1. Edge detection method

Being the dominant contribution in the uncertainty estimate of all intrinsic characteristics investigated in this work, some factors that may introduce non-negligible bias between CT-based data and tactile CMM data are presented.

First, there is an explicit difference between the surface extraction principle related to tactile CMM and CT-based data. The first method identifies the surface by physically contacting it (thus subjected to mechanical filtering). The latter determines the surface by assigning a threshold grey value to the 3D voxel data, which is affected by magnification errors.

Image artefacts caused by beam hardening and scattering may disturb correct surface detection, as they change the grey value of the edge pixels, and thus affect the identification of threshold values. Image blurring and noise also introduce threshold and interpolation errors [6].

Surface determination based on the 'iso-50%' threshold value applied globally, which represents the average value between the background peak and the material peak on the grey value histogram, may result in an edge offset errors with respect to the actual material edge.

In fact, the effect of beam hardening artefacts combined with the global threshold value could be identified in this study, by comparing the bias for external and internal features: positive bias for  $D_1$ , negative bias for  $D_2$  and  $D_3$  (see table 3).

**Table 3.** Standard uncertainties and bias for each intrinsic characteristic (values in millimeters).

Component	Intrinsic characteristic		
	$D_1$	$D_2$	$D_3$
$u_{cal}$	0.0010	0.0010	0.0010
$u_p$	0.0010	0.0010	0.0010
$u_b^{(1)}$	0.0002	0.0002	0.0001
<b><math>U_1 (k = 2)</math></b>	<b>0.003</b>	<b>0.003</b>	<b>0.003</b>
bias, $b$	0.021	-0.007	-0.023
<b><math>U_2 (k = 2)</math></b>	<b>0.043</b>	<b>0.014</b>	<b>0.046</b>
$ b  / U_2$	49.9%	48.9%	49.9%

<sup>(1)</sup>  $u_b = D_i \cdot (T - 20 \text{ }^\circ\text{C}) \cdot u_\alpha$   
with  $\alpha = 92 \cdot 10^{-6} \text{ }^\circ\text{C}^{-1} \pm 15\%$  and  $T = (20.8 \pm 0.2) \text{ }^\circ\text{C}$

## 5. Concluding remarks

The experimental uncertainty assessment of CT-based measurements using ISO 15530-3 approach has been shown effective for simple parts, and thus has been extended for other measurement cases in the laboratory routine. The good short-term repeatability observed in CT measurements and the relevant role played by the bias, are in consonance with results reported by other authors [6-7].

The estimated biases, clearly affected by edge-related determination errors, lie within the empirical error band proposed by the authors in a recent paper [4], and therefore reinforce their estimation. This error band has been proven fairly representative and acceptable for most dimensioning tasks performed on parts with similar shape and material.

## References

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