Avaliação experimental da incerteza associada ao resultado de medições de elementos de tamanho com tomografia computadorizada

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

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Resumo: O uso da tomografia computadorizada como técnica de medição dimensional tem se evidenciado nos últimos anos. Em função do complexo sistema de causas do erro de medição, não é trivial expressar a incerteza associada ao resultado de uma medição por tomografia. Neste artigo, investiga-se o uso do método experimental descrito na ISO 15530-3 para estimar a incerteza associada ao resultado da medição de elementos de tamanho, e os pontos mais importantes são apresentados e discutidos.

Palavras-chave: tomografia industrial, incerteza de medição, método experimental, elementos de tamanho.

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 uncertainty reporting has been made. The ISO 15530-3 experimental approach, which uses calibrated parts, has been tested for estimating the uncertainty of CT-based measurements of features of size. The most significant findings are outlined and discussed in this paper.

Keywords: industrial tomography, measurement uncertainty, experimental approach, features of size.

1. INTRODUCTION

Industrial computed tomography (CT) has been part of dimensional quality control loop for about a decade. In general, complex-shaped parts with hundreds (or 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 principle relies on the attenuation of X-rays when propagating through the test object, which depends on the test object material and size. 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 data. Further processing steps over the voxel data allow performing dimensional measurements.

The CT working 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 is 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 presents 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. Three intrinsic characteristics were defined according to the technical drawing of the 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.

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.

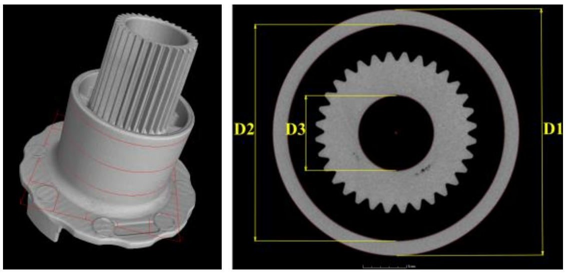

Figure 1. Illustrative image of the test object and the intrinsic characteristics (features of size).

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 ± 0.3) °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.

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

Feature	Calibration results
D_1	28.211 ± 0.002 (k = 2)
D_2	24.784 ± 0.002 (k = 2)
D_3	8.612 ± 0.002 (k = 2)

3.2. CT measurements

The test objected 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 kept at (20 ± 1) °C. The CT system manufacturer specifies a MPE for length measurements of (9 + L/50) µm, 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].

To scan the test object, the magnification axis was positioned to project the artefact using the maximum possible area of the detector (and thus reducing the voxel size). The source voltage was set high enough to avoid beam extinction, and detector integration time set to a convenient value. The source current was then set to enhance image contrast / 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 settings chosen for scanning the test object.

Parameter	**Unit**	**Value**
Source voltage	kV	110
Source current	µA	450
Focal spot size	µm	50
Integration time	s	1
Detector binning	--	2x2
Magnification	--	7.53
Voxel size	µm	53
No. of projections	--	800

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.

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

	Intrinsic characteristic		
Component	**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
U_1 (k = 2)	**0.003**	**0.003**	**0.003**
bias, b	0.021	-0.007	-0.023
U_2 (k = 2)	**0.043**	**0.014**	**0.046**
|b| / U_2	49.9%	48.9%	49.9%

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

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 [4], 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 [5].

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).

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 [5-6].

The estimated biases, clearly affected by edge determination errors, lie within the empirical error band proposed by the authors in a recent paper [7], and therefore reinforce their estimation. This error band have been proven fairly representative and acceptable for most dimensioning tasks performed on parts with similar shape and material.

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