Experimental assessment of computed tomography dimensional performance using modular test pieces made of polyoxymethylene and aluminum

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Abstract
Computed tomography for dimensional metrology has been part of the quality control loop for more than a decade. Because of the complex measurement-error cause system and the lack of appropriate guidance, usually no consistent uncertainty reporting has been made. Modular test pieces made of polyoxymethylene and aluminum have been devised, manufactured and used to investigate some influence factors intrinsic to CT-based data and their effects on evaluating features of size. The experimental planning and the most significant experimental findings, including the use of artefact reduction algorithms, are presented and discussed in this paper.

Keywords: computed tomography, measurement uncertainty, features of size, modular test pieces

1 Introduction
Computed tomography (CT) for coordinate metrology has been part of the dimensional quality control loop for about a decade. Complex-shaped parts with hundreds (or even thousands) of features can be inspected with great operational advantages over other existing technologies. CT measurement principle relies on the attenuation of X-rays when propagating through the part, which depends on part material and radiographic thickness. For a great number of beam directions, the intensity distribution of the remaining radiation is determined and digitally stored as a grey-value image. The resulting projections of full part rotation are processed to form the 3D voxel data. Further processing steps over the voxel data allow dimensional analyses.

Typical design of metrological CT scanners comprises the X-ray source at one end and the flat panel detector at the other end. Between them, a turntable for stepwise rotation of the part is placed, which can be linearly moved along the magnification axis. Many factors may influence the quality of dimensional evaluations, related to the source (e.g. photon energy, focal spot size), detector (e.g. sensitivity, pixel size, exposure time), part (e.g. material, geometry), CT kinematics (e.g. magnification axis and turntable accuracy), and mathematical data processing (e.g. artefact correction, surface determination, measuring strategy) [1].

Due to the intricate measurement-error cause system and scarcity of a convenient method to assess the uncertainty of CT-based measurements, no consistent uncertainty reporting has been made thus far. To handle this issue, particularly for features of size and distances, massively presented in parts received for dimensional analysis, modular test pieces made of aluminum and POM (polyoxymethylene) have been devised, manufactured and measured to explore the error behaviour of CT-based measurement data. This paper outlines and discusses the experimental design and the most relevant experimental findings of that study.

Figure 1: Set of three modular test pieces made of polyoxymethylene and aluminum used to analyse the error behaviour of CT-based data.
2 Experiment planning

Despite the large amount of factors that may contribute to measurement inaccuracy, from the dimensional metrology point of view, somehow they interact with each other to produce edge-offset errors, magnification errors, random errors, and localized structures [2]. Figure 1 illustrates the modular test pieces designed for studying those influences [3]. Each part consists of two cylindrical surfaces (internal and external) for quantifying random errors and edge offset errors; one pattern of four holes for separating edge offset errors from the magnification errors; and threaded pins with different diameters to allow varying the penetration length without changing the intrinsic characteristics under analysis.

2.1 Intrinsic characteristics

Considering the modular test piece design and study particularities, the following intrinsic characteristics were specified:

(a) Diameter of the external circumferential line at surface mid-height, \( D_1 \);
(b) Diameter of the internal circumferential line at surface mid-height, \( D_2 \);
(c) Diameter of the circle associated to centres of the hole pattern, \( D_3 \);
(d) Form of the external circumferential line at surface mid-height, \( R_1 \);
(e) Form of the internal circumferential line at surface mid-height, \( R_2 \).

2.2 Reference measurements

The intrinsic characteristics of each modular test piece have been calibrated on a Carl Zeiss PRISMO ultra coordinate measuring machine housed in a temperature-controlled laboratory kept at \((20.0 \pm 0.3) \, ^\circ C\). All diameters have been realized by associating ideal features of type circle to the scanned points using the least-squares association method. The root-mean-square roundness error has been used to estimate the form errors. Measurement uncertainties have been estimated using the Virtual CMM software output and expert judgment. Table 1 summarizes the calibration results for each modular test piece (material: POM or ALU, size in millimeters: 40, 60 or 90).

<table>
<thead>
<tr>
<th>Intrinsic Characteristic</th>
<th>POM40</th>
<th>POM60</th>
<th>POM90</th>
<th>ALU40</th>
<th>ALU60</th>
<th>ALU90</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_1 )</td>
<td>39.9236 ± 0.0015</td>
<td>60.0145 ± 0.0015</td>
<td>90.1972 ± 0.0015</td>
<td>40.2645 ± 0.0015</td>
<td>60.1785 ± 0.0015</td>
<td>90.0777 ± 0.0015</td>
</tr>
<tr>
<td>( D_2 )</td>
<td>16.2692 ± 0.0015</td>
<td>36.4101 ± 0.0015</td>
<td>65.9199 ± 0.0015</td>
<td>16.4991 ± 0.0015</td>
<td>35.9626 ± 0.0015</td>
<td>66.0957 ± 0.0015</td>
</tr>
<tr>
<td>( D_3 )</td>
<td>28.0062 ± 0.0025</td>
<td>47.9945 ± 0.0025</td>
<td>77.8573 ± 0.0025</td>
<td>27.9984 ± 0.0025</td>
<td>47.9907 ± 0.0025</td>
<td>77.9991 ± 0.0025</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>0.0012 ± 0.0010</td>
<td>0.0016 ± 0.0010</td>
<td>0.0028 ± 0.0010</td>
<td>0.0003 ± 0.0008</td>
<td>0.0002 ± 0.0008</td>
<td>0.0002 ± 0.0008</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>0.0011 ± 0.0010</td>
<td>0.0026 ± 0.0010</td>
<td>0.0031 ± 0.0010</td>
<td>0.0005 ± 0.0008</td>
<td>0.0003 ± 0.0010</td>
<td>0.0003 ± 0.0008</td>
</tr>
</tbody>
</table>

Table 1: Calibration results for the intrinsic characteristics of each test piece (best estimates and expanded uncertainties in millimeters).

2.3 Study setup

The dimensional analysis presented in this paper is a continuation of a recent work of the authors, presented at the XXI IMEKO World Congress, which restricted the investigation to modular test pieces made of POM. That study setup consisted of measuring the test pieces many times, varying some of the CT control settings or influencing factors that could be chosen or be under influence of the CT system operator, and then evaluating their effects on measured features’ dimensional content. From a so-called base parametrization, conditions that change the focal spot size and the voxel size have been modified, such as source current; detector integration time and resolution; magnification factor and number of angular poses. The main lessons learnt from that work for reliable dimensional analysis of features of size are repeated here [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.

Experiments have been carried out on a Carl Zeiss METROTOM 1500 CT scanner equipped with a 225 kV micro-focus tube and a 2048² pixels flat panel detector. Due to the dimensional metrology application, the CT scanner is housed in a laboratory kept at \((20 \pm 1) \, ^\circ C\). The CT system manufacturer states a maximum permissible error for length measurements of \((9 + L/50) \, \mu m\), using a test piece consisting of 27 ruby spheres mounted on carbon fibre shafts, and then determining the sphere-centre to sphere-centre distances of several pairs of spheres [5]; which on the other hand disregards the material influence [6]. This paper expands the experimental design to modular test pieces made of aluminum and considers the lessons learnt from the previous study. Thus, only the base parameterization has been investigated in this work, in which: the magnification axis has been positioned to project the part using the maximum possible area of the detector (reducing the voxel size); the filter plate thickness has been selected in accordance with the operating instructions of the CT scanner; the source voltage has been set high enough to avoid complete beam absorption, and detector integration time (and sensitivity) set to convenient values; the source current has been then tuned to enhance image contrast and brightness; the number of angular poses has been selected as approximately the number of pixel covered by the shadow of the part in the projection.
When adding pins to modify the penetration length, adjustments in source voltage and current have been made to properly redefine the grey value distribution. Regarding the surface definition from the voxel dataset, the standard ‘iso-50%’ threshold value has been applied globally. From the material boundary defined, 3600 points evenly spaced around the circumferential line have been extracted for each intrinsic characteristic, and the ideal feature of type circle associated to those points, using the least-squares fitting method. Table 2 lists the CT control parameters and values applied for each modular test piece, where the label after the modular test piece material/size indicates the threaded pin diameter (0: no pin; 1: pin of diameter 10 mm; 2: pin of diameter 30 mm; 3: pin of diameter 60 mm).

<table>
<thead>
<tr>
<th>Part / Setup</th>
<th>V</th>
<th>I</th>
<th>S</th>
<th>t</th>
<th>R</th>
<th>P</th>
<th>Vx</th>
</tr>
</thead>
<tbody>
<tr>
<td>POM40.0.001</td>
<td>110</td>
<td>450</td>
<td>50</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>53</td>
</tr>
<tr>
<td>POM40.1.001</td>
<td>110</td>
<td>450</td>
<td>50</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>53</td>
</tr>
<tr>
<td>POM60.0.01</td>
<td>120</td>
<td>450</td>
<td>54</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>73</td>
</tr>
<tr>
<td>POM60.1.01</td>
<td>130</td>
<td>450</td>
<td>58</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>73</td>
</tr>
<tr>
<td>POM60.2.01</td>
<td>130</td>
<td>350</td>
<td>46</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>73</td>
</tr>
<tr>
<td>POM90.0.01</td>
<td>140</td>
<td>450</td>
<td>63</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>106</td>
</tr>
<tr>
<td>POM90.1.01</td>
<td>140</td>
<td>450</td>
<td>63</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>106</td>
</tr>
<tr>
<td>POM90.2.01</td>
<td>140</td>
<td>500</td>
<td>70</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>106</td>
</tr>
<tr>
<td>POM90.3.01</td>
<td>140</td>
<td>500</td>
<td>70</td>
<td>1.0</td>
<td>1024²</td>
<td>800</td>
<td>106</td>
</tr>
</tbody>
</table>

Table 2: Control parameters and values used for studying the CT dimensional measurement performance, where: V. Source voltage [kV]; I. Source current [µA]; S. Focal spot size [µm]; F. Filter plate thickness [mm]; t. Sensor integration time [s]; R. Sensor resolution [pixel]; P. Number of projections; Vx. Voxel size [µm].

2.4 Data analysis

In order to evaluate the experimental data and comprehend how different volumetric matrices behave for each measured feature, target average (bias) control chart and range control chart have been employed. These control charts allow verifying the statistical consistency of measured biases (from the reference measurement results) and variances for different CT settings (averages and ranges taken from three repeated measurements on each part/setup). The charts will evidence causal differences among the estimates, lowering the risk of wrong decisions about CT measurement accuracy.

2.5 Good metrology practices

To allow the parts be easily and accurately positioned on the CT turntable, a stable mounting featuring a type II Kelvin clamp was designed and manufactured. The test pieces were orientated as illustrated in Figure 2, with the revolution axis of the part parallel to the rotation axis of the turntable. During measurements, the test piece temperature inside the CT cabinet was monitored in order to properly correct its effect in the dimensional measurements. Due to higher radiation energy requirements, the dimensional content of aluminum test pieces has also been evaluated after applying beam-hardening reduction algorithms.

Figure 2: Kinematic reference system with magnets, for easy, fast and repeatable mounting of the test piece (left) and projection (right).

3 Experimental findings

In this section, the most relevant findings for the intrinsic characteristics (described in 2.1) of the modular test pieces made of aluminum are graphically illustrated and analysed using target average control charts and range control charts.

3.1 Diameter of the external circumferential line, D1

In Figure 3, the range chart on the left shows that no point is beyond the upper control limit, and thus a standard deviation on the order of 0.002 mm (without applying beam-hardening reduction algorithm) can be estimated. The estimated biases in the target average chart are clearly out of control, as the between-setup variation cannot be explained by the repeatability (i.e., within-setup variation). For the bias chart on the left, the bias clearly grows as the modular test piece size increases. The largest bias is observed for the largest test piece with the largest pin threaded. This is a direct consequence of beam-hardening and scattering artefacts, which can be reduced by applying some artefact correction algorithm. The impact of it on the dimensional content is displayed in the charts on the right. The range chart shows that no point is beyond the upper control limit, and thus a
standard deviation on the order of 0.004 mm can be calculated. The estimated biases in the target average chart are out of control, as the between-setup variation cannot be explained by the measurement repeatability. Though some bias values are closer to the zero line (beam hardening correction increases measurement accuracy); others are on the opposite side and much farther away from the zero line (beam hardening correction worsens measurement accuracy).

Figure 3: Control chart for biases (upper) and control chart for ranges (lower) for the diameter of the external circumferential line without applying beam-hardening reduction algorithm (left) and after applying beam-hardening reduction algorithm (right).

3.2 Diameter of the internal circumferential line, $D_2$

In Figure 4, the range chart on the left shows that no point is beyond the upper control limit, and thus a standard deviation on the order of 0.002 mm (without applying beam-hardening reduction algorithm) can be estimated. This value is similar to that calculated for $D_1$, since the least-squares association method was used for both diameters.

Figure 4: Control chart for biases (upper) and control chart for ranges (lower) for the diameter of the internal circumferential line without applying beam-hardening reduction algorithm (left) and after applying beam-hardening reduction algorithm (right).
Here also the estimated biases in the target average chart are clearly beyond the limits, since the within-setup variation cannot explain the between-setup variation. There is no clearly bias correlation with the test piece size as for D₁. The largest biases are verified for ALU60.2.01 and ALU90.3.01 (with the largest possible pins). There is nearly no change in the dimensional content after applying the beam-hardening reduction algorithm. Both charts on the right of Figure 4 display very similar patterns when compared with data without artefact correction. For the largest test piece with the largest pin threaded, a significant increase in measurement accuracy could be checked; though very far from the zero bias line.

3.3 Diameter of the hole pattern, D₃

For the diameter of the circle associated to centres of the hole pattern, in principle, not influenced by edge offset errors, the range control chart displayed in Figure 5 is under statistical control. The estimated bias in the target average chart is again out of control, displaying three distinct layers, one for each modular test piece: bias of ca. 0 mm for ALU40; bias of ca. 0.01 mm for ALU60; bias of ca. -0.02 mm for ALU90 (except for the largest test piece with the largest pin attached). There is nearly no change in the dimensional content after applying the beam-hardening reduction algorithm for ALU40 and ALU60. Significant change could be observed for ALU90, despite not improving the measurement accuracy.

3.4 Roundness of the circumferential lines, R₁ and R₂

In Figures 6 and 7, the range charts display no point is beyond the upper control limit. The estimated biases in the target average chart are clearly out of control, since the between-setup variation cannot be explained by the within-setup variation. In fact, the form error is limited by the voxel size (i.e. the higher the voxel size, the higher the form error). There is no significant increase in measurement accuracy when applying the beam-hardening correction.

The roundness value of the external and internal circumferential line is dominated by the background noise presented in the CT data. When compared with the reference roundness value, a factor of ten could be evidenced, which might jeopardize profile and form evaluations, including CAD comparison, and any other analysis which relies on the extreme points.

4 Discussion and further analyses

Thus far, the first inference that could be drawn from this research has been the dimensional content behaviour before and after applying beam hardening reduction algorithm. In general, no relevant measurement accuracy improvement could be observed for most of the features. One exception is the diameter of the external circumferential line, in which some biases approach zero after applying the beam-hardening reduction algorithm (ALU40 and ALU60), even though others are much farther away from the zero line.

By plotting all biases on a single chart, as shown in Figure 8, one can observe that the lower variation limit is defined by the bias values related to the largest test piece with the largest pin attached (Figure 8, left). The reason for these extreme values needs to be further investigated. Removing them from the analysis, an overall variation on the order of ± 0.06 mm could be estimated. Being of systematic nature, they could be corrected using calibrated production pieces or accounted for in the
measurement uncertainty for parts with similar material and shape. This uncertainty range is about twice the range estimated for the POM modular test pieces [4], albeit expected due to the higher radiation energy requirements for scanning light metal parts, the critical role of filter plates and the later choice of the CT control settings.

Figure 6: Control chart for biases (upper) and control chart for ranges (lower) for the roundness of the external circumferential line without applying beam-hardening reduction algorithm (left) and after applying beam-hardening reduction algorithm (right).

Figure 7: Control chart for biases (upper) and control chart for ranges (lower) for the roundness of the internal circumferential line without applying beam-hardening reduction algorithm (left) and after applying beam-hardening reduction algorithm (right).

5 Concluding remarks and outlook
In principle, the error limit determined would be valid for the metrological CT system under test. That is a value beyond the maximum permissible error (MPE) stated by the manufacturer, as it is nearly insensitive to edge detection errors and material influence. Though more investigations may be needed to refine the error limit band, it is important to mention that generic uncertainty statements are in accordance with technical standards such as ISO 10012 and ISO 14253-2.
From the measurement application point of view, that error limit range would be more representative and reasonable for dimensioning tasks performed on aluminum parts, although not appropriate for some quality control operations (e.g., inspection of machined features). In those cases, the use of calibrated production aluminum parts as specified in part 3 of ISO 15530 would be recommended for estimating the task-specific uncertainty associated with feature-of-size measurement results. The resulting biases would improve the generic uncertainty statement made here. In any case, it should be borne in mind that the lesson learning process is also part of the uncertainty estimation task.

Regarding the use of ISO 15530-3 experimental approach, Müller et al. reported its use to estimate the uncertainty associated with some dimensional characteristics of a dose engine component made of brass and coated with a nickel layer [7], as well as the uncertainty associated with some dimensional characteristics of an aluminum pipe connector and a plastic toggle [8]. In addition, the CT measurement performance has been assessed by the authors of this paper using plastic production parts - please refer to other authors’ contributions [9-10]; and the estimated biases have lied within the empirical error band proposed [4]. Therefore, future researches would involve extending a similar approach to estimating the uncertainties associated with intrinsic characteristics of aluminum parts.

![Altogether Bias Chart (unfiltered)](image1.png)

![Altogether Bias Chart (filtered)](image2.png)

Figure 8: Plotting of all biases before (left) and after (right) removal of the values related to the largest test piece with the largest pin attached showing the measurement trend for distinct diameter characteristics.

References