Error sources analysis of computed tomography for dimensional metrology: an experimental approach

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Abstract
Computed tomography (CT) is a well-established non-destructive testing technique. In addition, in recent years it is becoming a consolidated method in the dimensional metrology field, offering important advantages over the traditional ones from the ability to perform internal and external measurements simultaneously and without contact. However, there are still some issues to overcome in terms of the CT reliability, traceability or measurement uncertainty determination, among others. The CT process for metrology applications is therefore complex and it is affected by many factors influencing its measurement uncertainty.

In this paper the influence of some sources of error has been studied from experimental work with an open CT system and a calibrated reference standard. A set of experiments has been developed comprising different elements, namely: surface extraction applied technique, CT acquisition parameters, detector type. From the results, both qualitative and quantitative conclusions about the influence of those parameters in the final accuracy have been obtained. Final conclusions establish upper limits to the uncertainties in the CT measurements and a detailed vision on the percentage of influence of the different sources of error to the global uncertainty value. This global data is found directly related with the image quality of the CT system, as expected.

Keywords: Computed tomography; Metrology; Design of Experiments; Canny

1. Introduction

X-ray CT is increasingly used in industry for dimensional metrology purposes. However, due to their complex and numerous error sources [1], the measurement results and metrological performance of CT systems are difficult to evaluate. Some approaches have been addressed in order to quantify the influence of every factor in the final measurement result. The CT Audit intercomparison presented in [2] is a perfect example of that. However, numerical relations between the scanning factors and the final accuracy of the results has not been established yet, partly due to the difficulty to actually access to the inner information of commercial CT systems.

In this paper an open CT system has been used to measure a calibrated reference standard according to a design of experiments (DOE) where different parameters have been varied and the error in some of the dimensions have been analysed as the objective functions, i.e. dimensions to be measured and whose measurement uncertainty should be minimum with the right combination of values of the measuring parameters. A set of experiments has been designed and developed in order to determine the influence and the limits for different sources of error. The principal error causes can be analyzed from two different approaches: software results from the surface extraction technique and acquisition parameters. Acquisition parameters apply to the X-ray source (energy, beam intensity, focus size) and to the detector/mechanical system (voxel size, system's magnification, number of projections). Image quality depends on these parameters, so a global influence on the uncertainty in CT metrology is clearly followed [3]. In this sense, a diversity of parameters have been varied for
the CT scans and analysis process for studying the largest error contributions along with the variability and robustness of the CT measurements.

2. Materials and methods

2.1 Reference standard and CT system

The reference standard used for the experiments consists of three ruby spheres of different diameters, made of synthetic ruby monocrystal and supported by a carbon fibre bar. The three diameters (D1, D2 and D3) and the distances between the centres of the three spheres (L12, L13, L23) have been previously calibrated by a CMM with 0.1 \( \mu \text{m} \) in resolution and a length MPE = 2.30 \( \mu \text{m} \) + (L/300) \( \mu \text{m} \) (L in mm). Their nominal values are shown in Figure 1 (left).

A general purpose 225 kV CT system (Figure 2) was used for the measurements, with both a linear and a flat panel detector (fan and cone beam geometry, respectively). The CT system has variable magnification, which allows the variation of the voxel size.

![Figure 1: Calibrated standard artefact nominal dimensions (left) and real image (right)](image1)

![Figure 2: CT system used (left) and reference standard placed in the CT system (right)](image2)

2.2 Measuring parameters

Different sets of parameters have been preliminary tested in order to select the most influential factors to be analyzed in the DOE. Consequently, the reference standard was initially measured by using:

- three different voltages (90 kV, 150 kV and 200 kV);
- two different sensors (a flat panel 2D sensor and a linear sensor);
two different angles of increment in the case of the flat panel (0.5 degrees and 0.4 degrees);

and two different surface extraction methods (an adaptive local optimal threshold determination method and a 3D Canny adapted method as described in [4]).

No physical filters were used for these parameters’ configuration, while the X-ray current was adjusted depending on the integration time and the energy for both detectors. Acquisition parameters (X-ray current, integration time, voxel size) were chosen for optimizing the detector signal and minimization of the image blurring. Chosen voxel sizes were 100 µm and 200 µm respectively for the fan beam and cone beam configuration.

From the points cloud and the subsequent reconstructed surface obtained after the surface extraction phase (Figure 3 left), a specific point selection strategy was used in order to obtain reliable points from the spheres and excluding any point of the carbon fiber bar (Figure 3 right). The compensation techniques explained in [4] were used to correct systematic errors and to properly calculate the scale factor.

![Figure 3: Spheres’ surfaces obtained from the CT scanning (left) and strategy for the selection of the points to be evaluated (right).](image)

All the three diameters (D1, D2 and D3), as well as the three distances (L12, L13, L23) were calculated and compared to the reference measurements obtained from the calibration. The standard deviation of the measurements and the form errors of all the three spheres were also included in the analysis.

### 2.3 Preliminary analysis

A preliminary design of experiments was carried out in order to decide the three main parameters to be formerly studied more in detail, as well as the approximate levels for each of them. Only one measurement was acquired with each of the combinations and no standard deviation was calculated. Therefore, the analyzed parameters in this preliminary DOE were: voltage, type of detector and surface extraction method. Their values are shown in Table 1 (i.e. 3 parameters and 2 levels per parameter):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Voltage (kV)</th>
<th>Type of detector</th>
<th>Surface extraction method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level -1</td>
<td>90</td>
<td>Linear</td>
<td>Local threshold</td>
</tr>
<tr>
<td>Level +1</td>
<td>150</td>
<td>Flat panel (angle of increment = 0.4º)</td>
<td>Canny adapted</td>
</tr>
</tbody>
</table>
From the obtained results, it was observed that all the studied dimensions (D1, D2, D3, L12, L13 and L23) showed a similar behavior regarding deviation with respect to the reference (i.e. systematic error) and standard deviation results. Consequently, the minimization of the deviations of D3 and L13 were selected as objective functions of the DOE analysis, since they showed representative results. Figure 4 shows the effect and the contribution after removing the effects of the interactions for both D3 and L13.

**Figure 4:** Effects and contributions obtained from the preliminary tests for deviation of D3 (left) and L13 (right)

The results obtained show that the main influence factor to decrease the deviation of both diameters (D3) and lengths (L13) is the detector type, showing the best results for the flat panel (Fig. 4). The surface extraction is the second term influencing the result, obtaining better results with the Canny adapted method for this type of dimensions. This same conclusion was also obtained in [5] for dimensions where the determination of the local threshold does not influence the final result, such as L12, L13 and L23.

For these dimensions, L13 and D3, the best results are obtained for 150 kV. The voltage contribution is similar for L13 and D3, and very low compared to the detector type and surface extraction method contributions. This effect can be explained from the geometry of the standard and its materials, which are quite permeable to X-rays thus limiting the influence of the acquisition voltage.

### 2.4 DOE parameters

From the conclusion of the preliminary analysis results, only the flat panel detector will be used for the full set of experiments. Therefore, the final DOE consists on acquisitions of the flat panel detector varying the energy (voltage) and for different projection's angle of increment. A higher voltage (200 kV) parameter will be used to test the interpolation, by analyzing if the 150 kV results can be extracted from a regression between 90 kV and 200 kV data.

Finally, the influence of the surface extraction method is studied in detail by repeating every measurement a number of times in order to check the variability and uncertainty of the measurements. Hence, the analyzed parameters in the final DOE are shown in Table 2 (3 parameters and 2 levels per parameter).
Table 2: Parameters and values used for the final DOE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Voltage (kV)</th>
<th>Angle of increment (°)</th>
<th>Surface extraction method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level -1</td>
<td>90</td>
<td>0.5</td>
<td>Local threshold</td>
</tr>
<tr>
<td>Level +1</td>
<td>200</td>
<td>0.4</td>
<td>Canny adapted</td>
</tr>
</tbody>
</table>

In this design of experiments, every combination is repeated five times, obtaining the systematic error - by comparing the measurement results with the calibrated values - for every studied dimension. In addition, the standard deviation from the five repetitions is also calculated and taken into account in the final analysis and in the uncertainty calculation.

2.5. Quality Image parameters

From the CT measurements it is possible to calculate some image quality parameters, as uniformity, SNR, contrast, noise and MTF. The calculation for these parameters follows the E144-01 Standard Guide for Computed Tomography Imaging, [6]. Obtained results are dimensionless and relative values, calculated for the reconstructed central slice of the middle sphere in the reference standard. Table 3 shows the relative normalized values.

Better image parameters are found for the highest energy (200 kV) and highest number of projections: SNR, contrast and noise (noise value is the lowest one). Uniformity, on the contrary, shows no relevant variation for the studied variables.

Table 3: Image quality parameters for the CT system, calculated from the CT images. Shown values are normalized to the maximum.

<table>
<thead>
<tr>
<th>Angle of increment</th>
<th>0.5 degrees</th>
<th>0.4 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>90 kV</td>
<td>150 kV</td>
</tr>
<tr>
<td>SNR</td>
<td>0.49</td>
<td>0.55</td>
</tr>
<tr>
<td>Uniformity</td>
<td>0.9973</td>
<td>0.9994</td>
</tr>
<tr>
<td>Contrast</td>
<td>0.46</td>
<td>0.53</td>
</tr>
<tr>
<td>Noise</td>
<td>1.00</td>
<td>0.98</td>
</tr>
</tbody>
</table>

3. Results

The results of the design of experiments for D3 and L13 are shown respectively in Figures 5 and 6. As pointed out before, the other measured diameters and lengths showed similar qualitative and quantitative results to those presented for D3 and L13. The effects and contributions of the tested parameters are shown in Figures 5 and 6, not only for single parameters but for parameter combinations. All the effects and contributions are represented in absolute values for a clear comparison.
Each influence parameter is separately analyzed below:

- **Surface extraction method influence.** The obtained results show that the main influence factor to decrease the deviation when measuring diameters, such as D3 (i.e. multidirectional measurement) is clearly the surface extraction method (Figure 5). The best results are obtained with the Canny adapted method for this type of dimensions, as expected from the preliminary tests. However, the influence of the surface extraction method is lower for L13 (Figure 6) than for D3. It should be pointed here that this same conclusion was also obtained in [5] for those dimensions where the determination of the local threshold does not influence the final result, such as L12, L23 and L13.

- **Voltage influence.** For both, L13 (i.e. a unidirectional measurement) and D3, slightly better results are obtained when using 200 kV, with the same behavior for 150 kV in comparison with 90 kV. In both cases, the contribution of the kV influence is similar.

- **Angle of increment influence.** Regarding the angle increment, a similar behavior to the voltage influence is observed: a low influence is found in the final result and with lower deviations obtained for 0.4 degrees in angular increment, instead of 0.5.
The analysis of variance shows that the best repeatability results are obtained when using the flat panel detector and the Canny adapted surface extraction method, with no relevant influence either from the voltage or the angle of increment. The values of the systematic errors (i.e. deviations with respect to the reference) and measurement uncertainty (for a 95% confidence level) are shown in Table 4 for D3 and L13, considering the best combination of parameters obtained in terms of minimum systematic error and standard deviation.

**Table 4: Systematic error and measurement uncertainty for D3 and L13 with the best combination of parameters found**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Detector</th>
<th>Voltage (kV)</th>
<th>Angle of increment (º)</th>
<th>Surface extraction method</th>
<th>Systematic error (µm)</th>
<th>Uncertainty $U_{95}$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3</td>
<td>Flat panel</td>
<td>150</td>
<td>0.4</td>
<td>Canny adapted</td>
<td>0.7</td>
<td>3.2</td>
</tr>
<tr>
<td>L13</td>
<td>Flat panel</td>
<td>150</td>
<td>0.4</td>
<td>Canny adapted</td>
<td>4.0</td>
<td>7.8</td>
</tr>
</tbody>
</table>

The measurement uncertainty values shown in Table 4 have been calculated according to the ISO 15530-3 standard [7]. Therefore, expanded uncertainty $U_{95}$ has been estimated by using Equation 1, extracted from [7].

$$ U_{95} = k \times \sqrt{u_{\text{cal}}^2 + u_p^2 + u_b^2 + u_w^2} $$  

**Table 5: Uncertainty contributions and maximum expanded uncertainty ($U_{95}$, k=2) obtained for the selected dimensions**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>D3 [µm]</th>
<th>L13 [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{\text{cal}}$</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>$u_p$</td>
<td>0.9</td>
<td>3.6</td>
</tr>
<tr>
<td>$u_b$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$u_w$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$U_{95}$</td>
<td>3.2</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Calibration uncertainty ($u_{\text{cal}}$) for each dimension is calculated from its calibration uncertainty, obtained from the previous CMM measurements. The uncertainty contribution of the measurement procedure ($u_p$) is calculated from the standard deviation of each dimension results, from the tomography acquisition repetitions. $u_p$ is one of the most relevant contributions together with $u_{\text{cal}}$, (see Table 5). The uncertainty contribution due to environmental conditions variations ($u_w$) of the workpiece material has a low influence (lower than 0.5 µm) in the final combined uncertainty. The standard uncertainty of the systematic error ($u_b$) is evaluated according to [7] and has also a low influence (lower than 0.5 µm). In Table 4 the uncertainty contributors and maximum expanded uncertainty ($U_{95}$, k=2) obtained for D3 and L13 is shown.

Quality image parameters were calculated (see previous section) and best results are found for higher energy and the 0.4 degrees angle of increment, as it is expected from the fundamentals of CT image generation. It is worth pointing out the difference for the voltage optimal value, 150 kV for the system uncertainty. This can be understood as a consequence of the chosen surface extraction method for the measuring process.
4. Conclusions

A systematic technique for the influence analysis of measuring factors in CT has been presented. The flexibility of the open CT system allowed the use of different parameters for image acquisition, and the most influent ones have been determined both qualitatively and quantitatively for the reference standard measured. This technique has resulted in a very appropriate method to establish upper limits to the uncertainties in CT measurements. This detailed vision on the percentage of influence of the different sources of error to the global uncertainty value can be used as a reliable approach for a future Monte Carlo simulation, in order to determine the measurement uncertainty of general purpose CT systems.

The best combination of parameters for the standard artifact can be depicted from the design of experiments:

- A 2D flat panel detector;
- A voltage value equal to 150 kV;
- An angle of increment equal to 0.4 degrees;
- A 3D Canny adapted surface extraction method.

Not only the surface extraction method but the best image quality values can be found as the best combination of parameters, taking into account the difference on the optimal energy. Testing the image parameters can be found as a valuable step for future DOE in CT dimensional metrology applications.

Further work must be carried out in order to establish the robustness and reproducibility of the obtained results when other geometries and materials are measured. In addition, other parameters will be also studied and the regression and analysis of variance will provide valuable information for a further analysis of the measurement uncertainties.

References