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14th CIRP Conference on Computer Aided Tolerancing (CAT)

Quantifying the Contribution of Post-Processing in Computed Tomography Measurement Uncertainty

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Abstract

This paper evaluates and quantifies the repeatability of post-processing settings, such as surface determination, data fitting, and the definition of the datum system, on the uncertainties of Computed Tomography (CT) measurements. The influence of post-processing contributions was determined by calculating the standard deviation of 10 repeated measurement evaluations on the same data set. The evaluations were performed on an industrial assembly. Each evaluation includes several dimensional and geometrical measurands that were expected to have different responses to the various post-processing settings. It was found that the definition of the datum system had the largest impact on the uncertainty with a standard deviation of a few microns. The surface determination and data fitting had smaller contributions with sub-micron repeatability.

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Keywords: Computed Tomography, measurement uncertainty, post-processing uncertainty, assembly, metrology

1. Introduction

Computed Tomography (CT) is bringing about a profound change in the way that tolerance verification is performed in industry. CT allows the inner and the outer geometry of an object to be measured without the need for external access or destructive testing [1]. In addition, CT measurement time is independent of the number of features on an item to be measured [2]. These are significant advantages over coordinate measuring machines (CMMs) when working with complex parts and assemblies. However, CT measurements are influenced by more factors, and therefore have a higher uncertainty, than the measurements from a CMM. While many of these factors have been identified [1-3], they still have not been quantified due to the complex interactions between the factors and their variability over time. This makes it difficult to produce an accurate statement of overall measurement uncertainty, and therefore difficult to accept or to reject a part using CT. These limitations may ultimately slow the penetration of CT in industry. The current industrial CT literature focuses on traditional uncertainties such as the uncertainty due to traceability to standards, hardware performance (e.g. repeatability), the environment (e.g. temperature) and the workpiece (e.g. material and manufacturing variations, surface finish, etc.) [4-8]. However, uncertainty due to post-processing is a major concern. CT scanners produce stacks of X-ray projections. Software is used to reconstruct the object from the image stack and to separate it into individual components (if necessary). Measurands can then be defined for the reconstructed (and separated) model. There are many ways to perform these operations and several software packages that can be used. Thus, CT measurements are more dependent on the user's post-processing strategy and performance than other types of measurement. This study evaluates the extent to which three post-processing activities (surface determination, the definition of the datum system, and fitting) affect the accuracy of CT measurements.

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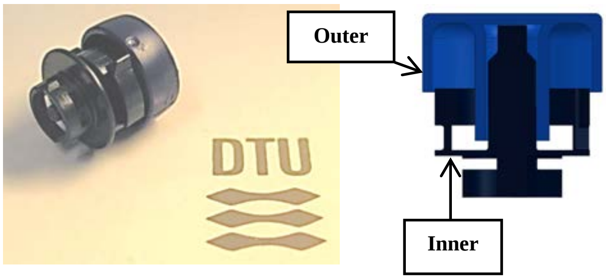
2. Workpiece and measurands

The measured workpiece is a two-part component from a commercial insulin injection device from Novo Nordisk A/S (figure 1a and b). The inner component is made of Polyoxymethylene. The outer component is made of ABS-polycarbonate. Information on materials is reported in table 1. Both components are produced via injection moulding. Only the outer component of the workpiece is considered in the investigation because it has the lowest absorption, and therefore is more challenging to scan and post-process. No deformations were expected in the inner component because of the clearance between the components in the areas of interest.



(a) (b)

Fig. 1. (a) the workpiece, (b) a 3D cross section representing the outer and inner component.

Table 1. Metrological information on materials comprising the workpiece.

Component	Density [g/cm^3]	Thermal expansion coefficient [10-6 K -1]
Inner	1.10	80 ± 20%
Outer	1.40	110 ± 20%

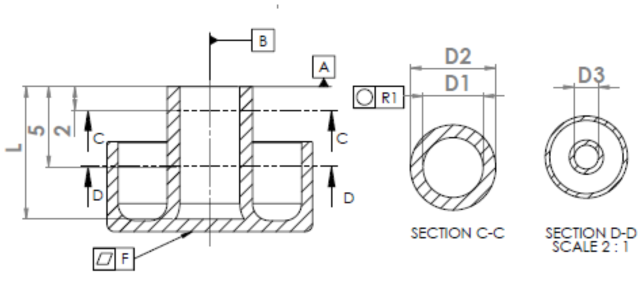


Fig. 2. The component and its datum system and measurands.

Six measurands (four dimensional and two geometrical measurands) were selected and shown in figure 2. D1 and D2 represent the inner and outer diameter of the smallest cylindrical feature measured at 2 mm below the datum A. D3 is the inner diameter of the smallest cylindrical feature measured at -5 mm from the datum A. R1 represents the roundness of D1, F stands for the flatness, measured at the bottom of the item (external surface). L corresponds to the distance between the top and the bottom of the inner component. These measurands were chosen in such a way as to provide a mix of features that are differently influenced by post-processing factors under investigation. Moreover, the positions of the measurands were selected in such a way as to generalize the results with respect to anisotropies in the measuring volume of CT, resulting from factors such as noise, the Feldkamp effect, the tilt of the rotary axis, and the anisotropy of the detector performance.

3. Process chain for post-processing evaluation

The investigation was carried out according to the procedure outlined in figure 3. After scanning and reconstructing the stack of X-ray projections, the CT voxel model was loaded in the inspection software and then inspected. The inspection was conducted using a measurement template. The template included all measurands except datum system (or alignment). After the measurands were extracted, the software was shut down and restarted to ensure the same set of initial conditions for post-processing. The procedure was replicated 10 times in order to have a representative sample. All analyses were performed on a singular CT voxel model to minimize the influence of other influence factors (mainly related to CT stability over time) on the investigation, but also in order not to introduce correlate errors between investigations. Nevertheless, the repeatability of CT was considered based upon experience. Statistical tools such as the Anderson-Darling test [9] and Chauvenet's criterion [9] were used to ensure the results against measurement errors such as outliers or mean drifts.

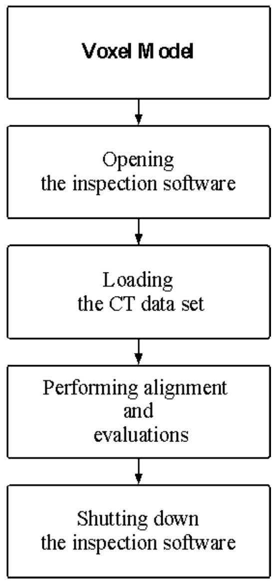


Fig 3. Measurement procedure used for the investigation. The procedure was replicated 10 times.

4. CMM and CT measurements and measurement uncertainties

4.1. Measurements on a tactile CMM

Tactile CMM measurements were used to validate the CT measurements using the En value [10]. The CMM measurements were performed using a Zeiss OMC 850 in a temperature-controlled laboratory (20 ± 1°C) with the temperature sampled constantly throughout the process. A 10-mm-long probe equipped with a 0.8-mm-diameter probing sphere was used for all the measurements. All measurements were repeated five times. The CMM evaluations were made with Calypso 5.4 software from Zeiss using a least square fit. The measurement uncertainty statements were provided according to [11]. Unless differently stated, a Type B evaluation of uncertainty was assumed [12] (equation 1):

$$U_D^{cal} = K * \sqrt{u_r^2 + u_p^2 + u_t^2} \quad (1)$$

where u_r is standard uncertainty associated with material standard (a ring reference artifact and a gauge block); u_p is the Type A evaluation of standard uncertainty of the measurement procedure; u_t is the evaluation of standard uncertainty due to the temperature variability (± 0.5°C) assuming a U-distribution; k is the confidence level coverage factor (k=2 for a coverage probability of 95 %). The same quantification of uncertainties was adopted for geometrical measurands except for the temperature contribution, which was not considered. The uncertainty quantification resulted in the values below 5 µm.

4.2. Measurement on an industrial CT scanner

The CT measurements were carried out at Novo Nordisk using a Zeiss Metrotom 1500. The XCT system was located in an air-conditioned laboratory with the temperature controlled to 20 ± 1°C and a relative humidity of 50% ± 10%. A measuring device was placed on the rotation table to record the temperature during measuring. This information was used for the correction of systematic error and for the measurement uncertainty statements. Note that since the temperature was recorded only at one spatial point, temperature gradients inside the measuring volume including the workpiece were not considered. However, it is reasonable to assume that the temperature is rather uniform within the limited measurement volume including the workpiece. The item was placed in a slightly tilted fixture to minimize the Feldkamp error [1]. The scanning parameters (table 2) were selected to stretch the available grey values in the histograms as much as possible, as a larger histogram produces better CT data. The spot size was kept as small as possible to avoid influencing the image sharpness. The number of projections, and therefore the scanning time, was chosen to limit the X-ray beam drift due to heat generation. The limited beam drift makes spot-drift-blurring negligible with respect to other blurring contributions. The magnification was selected as a compromise to reduce the border artifacts (most likely caused by the Feldkamp effect) while limiting the uncertainty contribution from the voxel size. No physical systematic error corrections (e.g. scale error correction) were done because the CT is equipped with guides and drives that produce a negligible scale error with respect to other systematic errors affecting CT.

Table 2. Scanning parameters used for the scan.

Parameter	Unit	Value	Parameter	Unit	Value
X-ray tube voltage	KV	100	Magnification		7
X-ray tube current	µA	390	No. of projections		1000
Voxel size	µm	40	Integration time	ms	1500
Spot size	µm	23	No. of images for projection		2

Software corrections (e.g. shading correction and beam hardening correction (BHC)) were automatically performed before and after scanning by the scanner. Neither beam hardening nor Feldkamp artifacts were observed on any surfaces (see, for example, figure 4). This led to grey value profiles across the workpiece (see, for example, figure 5), with a coefficient of variation [13] less than 0.14.

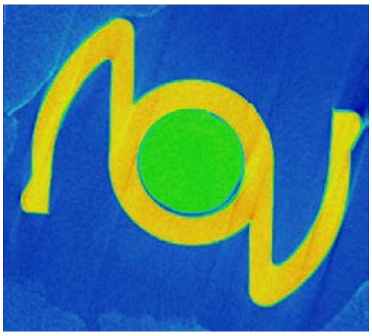


Fig. 4. Reconstruction slice, modified in Fiji image processing software, of the two-part component showing the complete absence of artefacts on the surfaces.

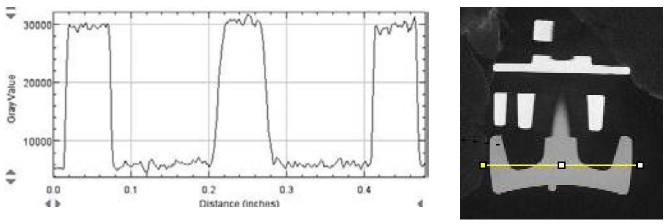


Fig. 5. Grey value profile (left) across the item at 0.11 mm from the bottom of the item (right).

VG studio max 2.2.6 was used for performing surface determination and evaluations. The CT voxel model was segmented using a local thresholding technique with a 3-voxel-search distance. This means that the software first finds a rough solution and then refines the latter across the search distance. The attention paid in selecting a correct search distance is generally rewarded by a more accurate surface determination, especially in the presence of a multi-material workpiece whose X-ray absorption coefficients are close to each other. The thresholding value of the local thresholding technique was manually defined during the first measurement, and afterward it was just replicated. This makes it possible to avoid modifying the surface determination in terms of systematic error and to consider only its variability. The evaluations were performed after having aligned the CT voxel data set using the same approach as the CMM datum system. The evaluations were performed using primitive features similar to those used during the calibration. The measurement uncertainties were calculated in the same way as the CMM measurements by taking into account the following influence contributions: traceability, repeatability, unsharpness, surface finish, and temperature. Unless differently stated, a Type B evaluation of uncertainty [12] was assumed according to equation 2.

$$U_D^{cal} = k * \sqrt{u_r^2 + u_p^2 + u_{res}^2 + u_s^2 + u_t^2} \qquad (2)$$

where u_r is standard uncertainty owing to traceability quantified by the MPE (9 µm + L/50), treated using a rectangular distribution, u_p is the standard uncertainty of the measurement procedure assumed to be 1.1 µm, based on the experience of the authors; u_{res} is the standard uncertainty due to the CT resolution, quantified as follows

$$u_{res} = \sqrt{u_f^2 + u_{rec}^2} \qquad (3)$$

Here, u_f and u_{rec} are the standard uncertainties associated with the focus spot size and the reconstruction blurring [14]. Those uncertainties were all quantified using a rectangular distribution. u_s is the standard uncertainty of the workpiece surface finish using Ra [15] treated using a rectangular distribution; and finally, u_t is the evaluation of standard uncertainty of the temperature deviation (± 1 ^{o}C) based on a U-distribution. The uncertainty quantification resulted in the values ranging between 11 and 15 µm confirming the accuracy gap between CT and a traditional CMM. Nevertheless, the CT and CMM measurements were found to be in agreement according to the En analysis. The dimensional measurements and the geometrical measurements were all found to be below the threshold condition (En <1), although the geometrical measurements were closer to the threshold.

5. Results

Table 3 lists the standard deviation value per measurand (σ_{10} of 10 measurements) and the average value of all standard deviations (σ_m). The latter was quantified assuming no correlation between the standard deviations. The results revealed discrepancies between the measurands that were and were not datum-system-dependent. This is likely because the datum system is established by feature datums, which are themselves measured and subjected to errors [16]. The fitting repeatability was found to be better than 0.5 µm. This quantification was obtained fitting 2 measurands 5 times within the same evaluation (and thus same alignment). Note that the same initial points were used thanks to two measurements templates. In contrast, the roundness and flatness measurement were characterized by larger variability over the 10 measurements. These results provide further evidence that the definition of the datum system is mainly responsible for this measurement variability. Surface determination was found to be as repeatable as the fitting due to the high uniformity of the grey value distribution representing the workpiece, and the near absence of a decision-making process by the operator. A worsening of the surface determination repeatability up to 2 µm was recorded when operator-based approaches were applied. No differences were seen between the similar measurands – diameters - placed at different heights or on different surfaces (inner and outer surfaces of smallest cylinder).

Table 3. Standard deviation value per measurand (σ_{10}) along with the mean of all standard deviations (σ_m). The values are rounded and expressed in µm.

Measurands	identification	σ_{10}
D1	Diameter (datum feature)	3
D2	Diameter	5
D3	Diameter (datum feature)	3
R1	Roundness	5
F	Flatness (datum feature)	2
L	Length	3
σ_m		**2.8**

The quantification of the datum system uncertainty was based on σ_m (type A evaluation of uncertainty). The datum system uncertainty was found to be comparable to the CT repeatability and the traceability contributions. Such a result may be somehow biased because all feature datums were treated as equally important. Then, a refinement of quantification of the datum system uncertainty was attempted weighting the various datums [16] as shown in equation 3.

$$u_{datum} = \sqrt{\frac{3}{6}u_3^2 + \frac{2}{6}u_2^2 + \frac{1}{6}u_1^2} \qquad (3)$$

where u_1, u_2, u_3 are the uncertainties for the primary, secondary and, tertiary datums. Those uncertainties were quantified using the standard deviation of each datum feature reported in the table. Despite the modelling effort, the refined uncertainty provides a 15% smaller contribution (2.5 µm) than the all-around estimation. This confirms the datum system is an important influence to consider. It is believed that the importance of the datum system uncertainty can be drastically scaled down reducing the noise level within the data set and or placing datum features on surfaces less affected by noise (e.g. surface in the center of the X-ray beam). The definition of datum features should also take into account the way in which CT works instead of adapting strategies used in traditional CMMs. This will be investigated further in future work.

6. Conclusions

This paper investigated the repeatability of the post-processing to make the quantification of uncertainty more realistic and reliable. The following conclusions can be drawn:

- The uncertainties of the CT measurements were found to vary between 11 and 15 µm. Such values are at least double the uncertainties of those from the CMM. Good agreement between the CT and CMM measurements was found according to En values.
- Surface determination was not found to be a source of influence because it was characterized by a very high repeatability (0.5 µm).
- Fitting algorithms were likewise found to be repeatable, even though in some cases a miss fitting was observed.
- The datum system was found to be the most prominent source of uncertainty in the investigation. This was observed using two different approaches to the quantification (2.8 or 2.5 µm). This makes the datum-related uncertainty as important as the repeatability and traceability of the CT.

Acknowledgements

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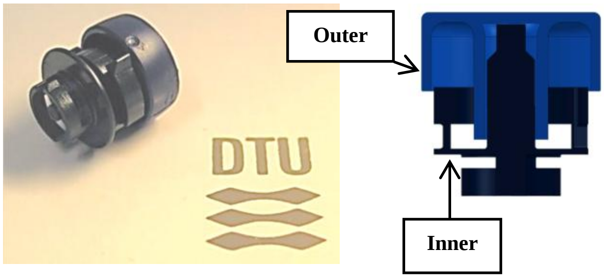

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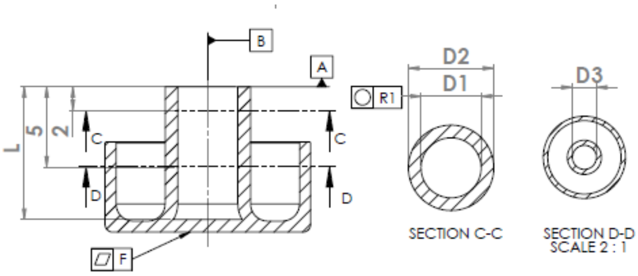

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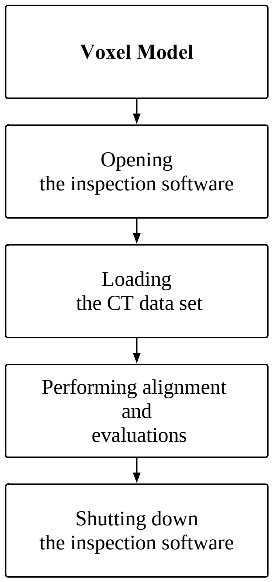

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Voxel size	µm	40	Integration time	ms	1500
Spot size	µm	23	No. of images for projection		2

Software corrections (e.g. shading correction and beam hardening correction (BHC)) were automatically performed before and after scanning by the scanner. Neither beam hardening nor Feldkamp artifacts were observed on any surfaces (see, for example, figure 4). This led to grey value profiles across the workpiece (see, for example, figure 5), with a coefficient of variation [13] less than 0.14.

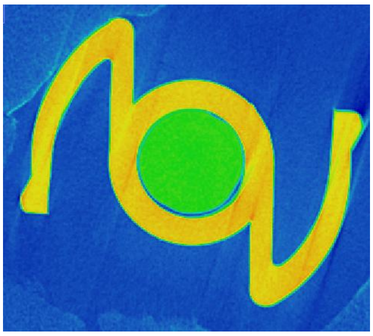

Fig. 4. Reconstruction slice, modified in Fiji image processing software, of the two-part component showing the complete absence of artefacts on the surfaces.

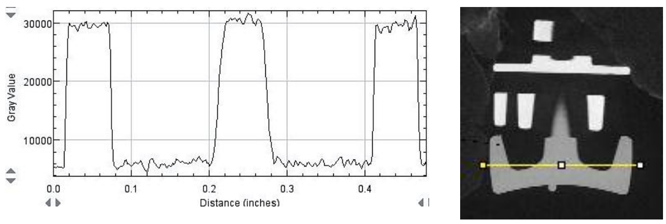

Fig. 5. Grey value profile (left) across the item at 0.11 mm from the bottom of the item (right).

VG studio max 2.2.6 was used for performing surface determination and evaluations. The CT voxel model was segmented using a local thresholding technique with a 3-voxel-search distance. This means that the software first finds a rough solution and then refines the latter across the search distance. The attention paid in selecting a correct search distance is generally rewarded by a more accurate surface determination, especially in the presence of a multi-material workpiece whose X-ray absorption coefficients are close to each other. The thresholding value of the local thresholding technique was manually defined during the first measurement, and afterward it was just replicated. This makes it possible to avoid modifying the surface determination in terms of systematic error and to consider only its variability. The evaluations were performed after having aligned the CT voxel data set using the same approach as the CMM datum system. The evaluations were performed using primitive features similar to those used during the calibration. The measurement uncertainties were calculated in the same way as the CMM measurements by taking into account the following influence contributions: traceability, repeatability, unsharpness, surface finish, and temperature. Unless differently stated, a Type B evaluation of uncertainty [12] was assumed according to equation 2.

$$U_D^{cal} = k * \sqrt{u_r^2 + u_p^2 + u_{res}^2 + u_s^2 + u_t^2} \qquad (2)$$

where u_r is standard uncertainty owing to traceability quantified by the MPE (9 µm + L/50), treated using a rectangular distribution, u_p is the standard uncertainty of the measurement procedure assumed to be 1.1 µm, based on the experience of the authors; u_{res} is the standard uncertainty due to the CT resolution, quantified as follows

$$u_{res} = \sqrt{u_f^2 + u_{rec}^2} \qquad (3)$$

Here, u_f and u_{rec} are the standard uncertainties associated with the focus spot size and the reconstruction blurring [14]. Those uncertainties were all quantified using a rectangular distribution. u_s is the standard uncertainty of the workpiece surface finish using Ra [15] treated using a rectangular distribution; and finally, u_t is the evaluation of standard uncertainty of the temperature deviation (± 1 °C) based on a U-distribution. The uncertainty quantification resulted in the values ranging between 11 and 15 µm confirming the accuracy gap between CT and a traditional CMM. Nevertheless, the CT and CMM measurements were found to be in agreement according to the En analysis. The dimensional measurements and the geometrical measurements were all found to be below the threshold condition (En <1), although the geometrical measurements were closer to the threshold.

5. Results

Table 3 lists the standard deviation value per measurand (σ_{10} of 10 measurements) and the average value of all standard deviations (σ_m). The latter was quantified assuming no correlation between the standard deviations. The results revealed discrepancies between the measurands that were and were not datum-system-dependent. This is likely because the datum system is established by feature datums, which are themselves measured and subjected to errors [16]. The fitting repeatability was found to be better than 0.5 µm. This quantification was obtained fitting 2 measurands 5 times within the same evaluation (and thus same alignment). Note that the same initial points were used thanks to two measurements templates. In contrast, the roundness and flatness measurement were characterized by larger variability over the 10 measurements. These results provide further evidence that the definition of the datum system is mainly responsible for this measurement variability. Surface determination was found to be as repeatable as the fitting due to the high uniformity of the grey value distribution representing the workpiece, and the near absence of a decision-making process by the operator. A worsening of the surface determination repeatability up to 2 µm was recorded when operator-based approaches were applied. No differences were seen between the similar measurands – diameters - placed at different heights or on different surfaces (inner and outer surfaces of smallest cylinder).

Table 3. Standard deviation value per measurand (σ_{10}) along with the mean of all standard deviations (σ_m). The values are rounded and expressed in µm.

Measurands	identification	σ_{10}
D1	Diameter (datum feature)	3
D2	Diameter	5
D3	Diameter (datum feature)	3
R1	Roundness	5
F	Flatness (datum feature)	2
L	Length	3
σ_m		**2.8**

The quantification of the datum system uncertainty was based on σ_m (type A evaluation of uncertainty). The datum system uncertainty was found to be comparable to the CT repeatability and the traceability contributions. Such a result may be somehow biased because all feature datums were treated as equally important. Then, a refinement of quantification of the datum system uncertainty was attempted weighting the various datums [16] as shown in equation 3.

$$u_{datum} = \sqrt{\frac{3}{6}u_3^2 + \frac{2}{6}u_2^2 + \frac{1}{6}u_1^2} \qquad (3)$$

where u_1, u_2, u_3 are the uncertainties for the primary, secondary and, tertiary datums. Those uncertainties were quantified using the standard deviation of each datum feature reported in the table. Despite the modelling effort, the refined uncertainty provides a 15% smaller contribution (2.5 µm) than the all-around estimation. This confirms the datum system is an important influence to consider. It is believed that the importance of the datum system uncertainty can be drastically scaled down reducing the noise level within the data set and or placing datum features on surfaces less affected by noise (e.g. surface in the center of the X-ray beam). The definition of datum features should also take into account the way in which CT works instead of adapting strategies used in traditional CMMs. This will be investigated further in future work.

6. Conclusions

This paper investigated the repeatability of the post-processing to make the quantification of uncertainty more realistic and reliable. The following conclusions can be drawn:

- The uncertainties of the CT measurements were found to vary between 11 and 15 µm. Such values are at least double the uncertainties of those from the CMM. Good agreement between the CT and CMM measurements was found according to En values.
- Surface determination was not found to be a source of influence because it was characterized by a very high repeatability (0.5 µm).
- Fitting algorithms were likewise found to be repeatable, even though in some cases a miss fitting was observed.
- The datum system was found to be the most prominent source of uncertainty in the investigation. This was observed using two different approaches to the quantification (2.8 or 2.5 µm). This makes the datum-related uncertainty as important as the repeatability and traceability of the CT.

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