Using Calibrated Parts and Integral Surface Analysis to Investigate Dimensional CT Measurements

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Abstract. The application of computed tomography (CT) is growing rapidly in the field of dimensional metrology. In the current state of the art, however, CT-systems cannot provide the same accuracy as tactile coordinate measuring systems, and one of the main reasons is the high level of noise generated in CT measurements. This paper presents an experimental approach to investigate the influence of the extraction operation on geometrical evaluations performed with CT-systems. The methodology consists in performing systematic experiments using different setup parameters on calibrated workpieces; and comparing characteristics of the extracted integral features in both the space and the frequency domains. The approach was used to analyse a set of CT measurement data extracted with different setup parameters and evaluated with different verification operators. The results demonstrate that distortions generated during the extraction operation with CT systems may have great impact on the results of geometrical evaluations. In this context, the analysis of the integral extracted features obtained with systematic experiments showed to be a useful tool to evaluate the quality of the extraction operation, and thus, to define the setup parameters in order to improve the accuracy of geometrical evaluations.

1. Introduction

Recent developments have contributed to expand the application of computed tomography (CT) to the field of dimensional metrology. The main attractiveness of this technology is the possibility of a holistic approach enabling both material and geometrical inspection of external and internal features, with high data density. In the industrial context, CT-systems may be used to provide information regarding the actual state of products and processes, based on which important decisions concerning the quality of the goods are made. For instance, a CT-system may be used for the inspection of geometrical deviations produced by the manufacturing process, which (ideally) indicates if the real part complies with the functional requirements defined by the designer. For this task, CT measurements must be able to accurately detect the amount of imperfection on the workpiece that will affect its functions thus providing reliable and useful information for making decisions.

In the current state of the art, however, the measurement data obtained with CT-systems are not as accurate as the data obtained with, for instance, traditional tactile coordinate measuring machines (CMM). One of the causes of this difference relies on the measuring principles involved in generating the measurement data during the **extraction operation** (according to the GPS skin model [1],[2]).

For instance, in the case of most CMM, the extraction operation is performed by directly reading the Cartesian coordinates of the sensor for each extracted point, and performing some simple mathematical operations (e.g. tip radius correction). On the other hand, the extraction operation using CT-systems is a much more complex task, comprised of a number of intermediary operations, resulting in an intricate measurement chain (Figure 1).

The **image acquisition operation** is the first step, which comprises in taking a large number of x-ray projections acquired along rotation of the workpiece through 360°. Following, the **reconstruction operation** must be performed, which consists in applying a reconstruction algorithm (usually the filtered back projection [3]) to the projections, providing a volumetric image (voxel matrix) of the workpiece and its surroundings. Next step is to perform the **thresholding operation**, which defines the voxels that better correspond to the interface between the air and the workpiece (or between different materials), resulting in a "virtual surface" (digital skin model). Finally, the points that define the integral extracted features to be used in the geometrical evaluations must be chosen, which is usually performed by resampling the virtual surface with the so-called [4] "**virtual probing**" **operation**.

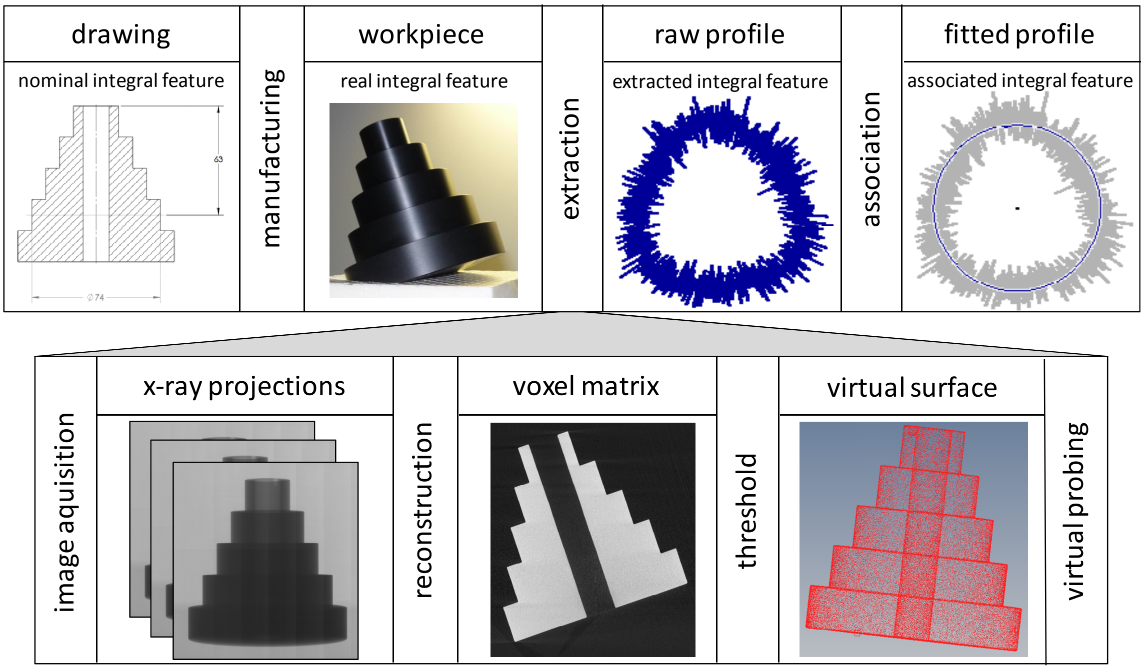

Figure 1. Example of the measurement chain for a diameter evaluation using a CT-system.

Associated with the steps of the extraction operation performed by a CT-system, several physical phenomena, mathematical transformations, hardware limitations (and their interactions) end up introducing distortions (measurement system induced deviations) in the resulting voxel matrix. For instance, phenomena like quantum noise, scattering and detector noise during the image acquisition produces random disturbances in the acquired projections [5]. The use of relatively large voxel sizes may lead to aliasing in the projections, which results in Moiré patterns in the voxel matrix; and the use of relatively small number of projections leads to aliasing artefacts (streaks) in the voxel matrix [6]. The overall distortion resulting from the combination of these (and other) disturbances affects the thresholding operation, ultimately leading to random noise[1] (besides systematic artefacts) integrated to the virtual surface. Finally, using inadequate sampling intervals on the virtual surface may also lead to additional aliasing in the extracted integral features.

[1] To avoid ambiguities, the use of the word "noise" from this point on will refer to the random (usually wide-band) dispersion of points produced by the extraction operation and observed in the integral extracted feature.

After the extraction operation, the remaining verification operations (such as filtering, association, collection, construction and evaluation) must be performed in order to obtain the value of the geometrical parameter of interest. The use of some verification operators may reduce the sensitivity of the geometrical evaluation to the presence of noise (e.g. using low cut-off frequencies for filtering operations or least square methods for association operations). Nevertheless, it is important to mention that the use of verification operators other than the specification operators (defined by the designer) should be avoided, as this introduces method uncertainty into the measurement uncertainty [7].

In the described scenario, it becomes clear that decisions made by the CT user regarding setup parameters are of great importance, as they will have direct influence on the magnitude of the above mentioned effects, and, as a result, indirect impact on the quality of the extracted integral features. Therefore, deciding on the setup parameters which will lead to an acceptable amount of extraction distortions according to the specification operators is a crucial task on achieving a proper accuracy for geometrical evaluations.

This paper presents an experimental approach used to investigate the influence of the extraction operation on geometrical evaluations performed with CT-systems. The methodology consists in performing systematic experiments using different setup parameters on calibrated workpieces; and comparing characteristics of the extracted integral features in both the space and the frequency domains. The approach was used to analyse a set of CT measurements performed on a workpiece having a calibrated circumferential line.

2. Materials and Methods

The workpiece selected for this study is a step cylinder machined in polyoxymethylene plastic (Figure 2). The feature to be extracted is a circumferential line located at 63 mm from the top plane, having a nominal diameter of 74 mm. The geometrical parameters to be evaluated are the diameter and the roundness deviation of the extracted circumferential line.

All the measurements were conducted on the same laboratory with controlled environmental temperature of (20 ± 1) ˚C, and no temperature compensation was performed for any of the measurements.

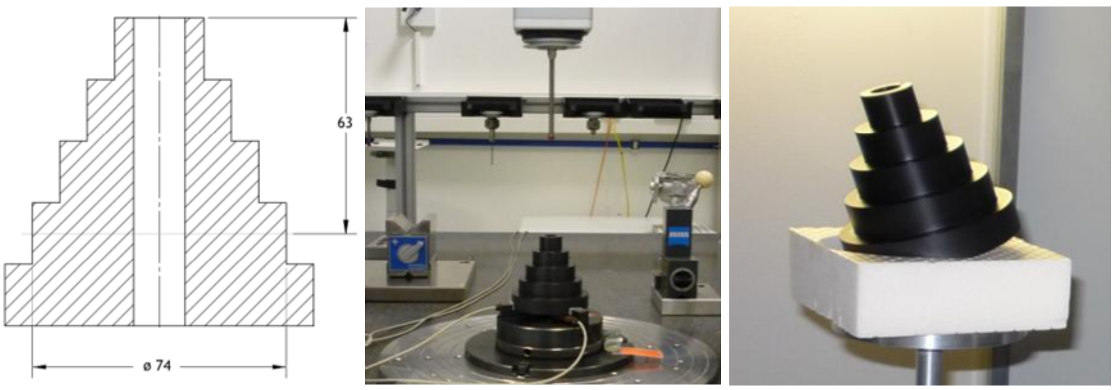

Figure 2. Evaluated feature (left); CMM workpiece setup (center); CT workpiece setup (right).

The calibration of the workpiece was performed by extracting circumferential lines with a tactile CMM[2] using the point-by-point measuring mode (231 points). A spherical tip stylus with a 3 mm diameter was selected for the task. Three measurement cycles were performed.

[2] ZEISS Prismo 7, $MPE_E = 2{,}5 + L/300$ µm, software Calypso v4.6.

The evaluated system was an industrial cone-bean CT-system[3]. The extraction of the circumferential lines was performed with using two different sets of setup parameters (Table 1). The difference between setup parameters relies on the voxel size (indirectly defined by the position of the step cylinder in relation to the detector), chosen in order to investigate the influence of the sampling interval on the quality of the voxel matrix.

Table 1. CT setup parameters.

Setup #	Voxel size *Vx [μm]*	Voltage *U [kV]*	Current *I [μA]*	Integration time *B [ms]*	Gain *E [pF]*	Pre-filters, Cu *V [mm]*	Projections *P*
1	**120**	225	100	2000	1,0	0,5	1080
2	**320**	225	100	2000	1,0	0,5	1080

All the extracted circumferential lines (with both CMM and CT-system) were exported as ASCII files by the measurement software and the remaining verification operations (filtering, association and evaluation) were performed with a dedicated application [8]. Besides the geometrical evaluations, this application performs an integrated graphical analysis in the space (polar plot) and in the frequency domain (harmonic content obtained with the FFT), which provides useful insight on the measurement process behaviour.

In order to investigate the influence of the extraction operation on the geometrical evaluations, the extracted circumferential lines (also called "raw profiles") were processed with two different verification operators for roundness evaluations and four different verification operators for diameter evaluations [9],[10]:

- RONt (LSCI, raw) – Peak-to-valley roundness evaluation referenced on a circle associated by least squares, both operations performed on the extracted circumferential line.
- RONt (LSCI, G15) – Peak-to-valley roundness evaluation referenced on the circle associated by the least squares, both operations performed on the roundness profile (linear Gaussian filtering with a cut-off frequency of 15 UPR).
- Diameter (LSCI, raw) – Diameter of the least squares circle associated on the extracted circumferential line.
- Diameter (LSCI, G15) – Diameter of the least squares circle associated on the roundness profile (linear Gaussian filtering with a cut-off frequency of 15 UPR).
- Diameter (MCCI, raw) – Diameter of the minimum circumscribed circle associated on the extracted circumferential line.
- Diameter (MCCI, G15) – Diameter of the minimum circumscribed circle associated on the roundness profile (linear Gaussian filtering with a cut-off frequency of 15 UPR).

The influence of the sampling interval used in the virtual probing operation was also investigated. This investigation was performed by probing the virtual surface obtained with Setup #1 using two different point densities. The first one was sampled with basis on the "seven times the cut-off frequency" criterion (15 UPR, 105 points) [10], and the second ones was sampled using the maximum number of points allowed by the measurement software for the given virtual surface (3600 points).

3. Results

The results of the investigations are presented in two sections: first, the analysis of integral circumferential lines obtained with different voxel sizes; and later, the analysis of the integral circumferential lines obtained with different virtual probing strategies.

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[3] ZEISS Metrotom 1500, MPE_E = 9 + L/50 μm, maximum photon energy of 225 keV, detector resolution of 1024 x 1024 pixel, software Calypso v5.0.

3.1. Analysis of the voxel size on the extraction operation

The results of the geometrical evaluations performed to investigate effects of the voxel size are compiled in Table 2 and in Figure 3. In general, significant differences can be observed between reference and CT measurements, between measurements performed with different setup parameters and evaluated with different verification operators.

Regarding the roundness evaluations, it can be noted that the RONt (LSCI, raw) values obtained with the CT-system resulted significantly higher than those obtained with the CMM. For the filtered profiles, the RONt values obtained with Setup #1 resulted much closer to the reference values than those obtained with Setup #2. It is also noticeable the large difference observed between raw and filtered CT profiles (~50 µm) when compared with the differences observed with the CMM (~2 µm).

For the diameter evaluations, one can see that the least squares circle (LSCI) values obtained with Setup #2 are closer to the reference values than the ones obtained with Setup #1. When the minimum circumscribed circle is used, the results obtained with the CT-system are equivalent (not considering differences between raw and filtered profiles). However, a large difference is observed between the CT values and the reference ones (~70 µm for the raw profiles, and ~20 µm for the filtered profiles). Finally, no difference is observed between raw and filtered profiles associated by least squares.

Table 2. Mean values obtained for the geometrical evaluations.

Verification operators	*CMM*	*CT setup 1*	*CT setup 2*
RONt (LSCI, raw)	0.0121	0.0610	0.0965
RONt (LSCI, G15)	0.0102	0.0124	0.0444
Diameter (LSCI, raw)	74.1352	74.1561	74.1387
Diameter (LSCI, G15)	74.1352	74.1561	74.1387
Diameter (MCCI, raw)	74.1475	74.2122	74.2138
Diameter (MCCI, G15)	74.1460	74.1673	74.1665

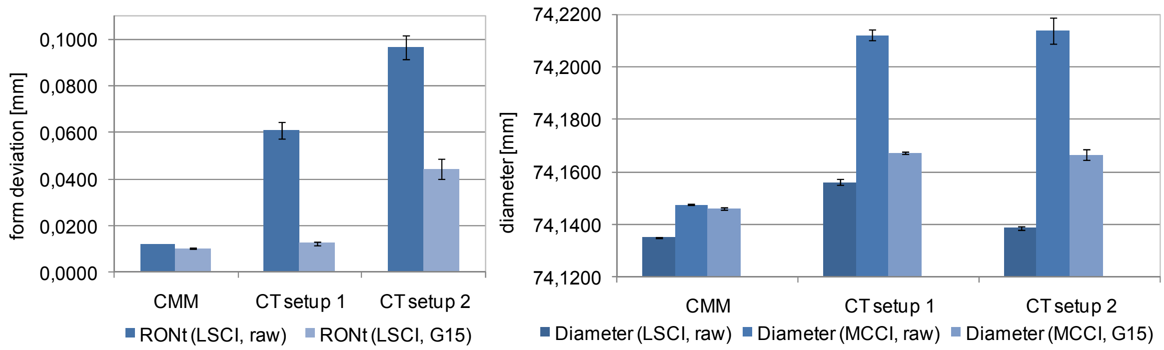

Figure 3. Mean values and maximum deviations from the mean obtained for the geometrical evaluations.

Despite the important remarks obtained with the above analysis, very little can be said about the causes of the observed differences. Much more information can be obtained with the analysis of the extracted circumferential lines, as presented in Figures 4-6.

By observing the reference profile obtained with the CMM (Figure 4), it is possible to notice that the workpiece presents a dominant harmonic with a 3 UPR frequency and amplitude of 5,1 µm. All the harmonics above 15 UPR present amplitudes of less than 0,1 µm, which indicates a relatively "clean" extraction operation (low level of noise generated), and also that no significant waviness (in relation to the dominant harmonic) is present on the surface of the workpiece. Given the limited number of sampled of points, it is possible that some aliasing have occurred during the extraction, but no evident effects can be observed.

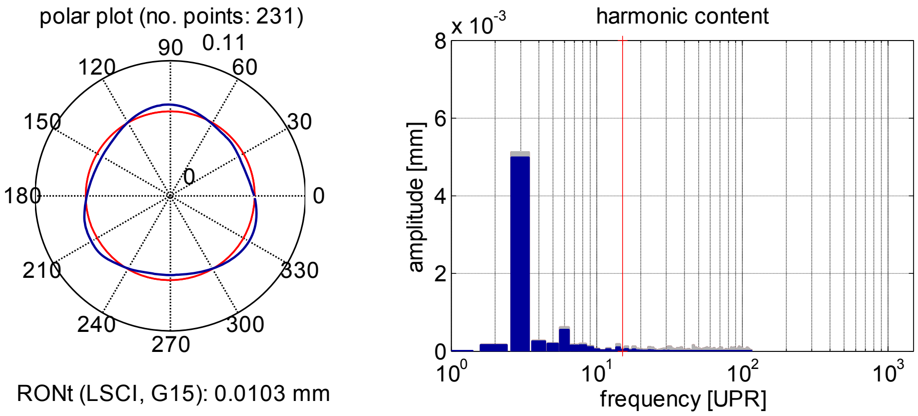

Figure 4. Reference profile obtained with the CMM. Extracted circumferential line (grey), roundness profile (blue), associated circle (red).

Regarding the CT measurements performed with Setup #1, it is possible to observe the occurrence of a high level of noise, which is not present on the reference profile (Figure 5). This noise explains the large differences observed in RONt (LSCI, raw) and Diameter (MCCI, raw) values between Setup #1 and CMM. It is not clear, however, if the observed noise (or how much of it) is result of aliasing occurrence. Furthermore, it can be noted that the noise disturbs also the lower frequencies of the spectrum, although not in a critical manner, so that the filtered profile reproduces relatively well the reference profile. This explains the similar RONt (LSCI, G15) values obtained with both measurement systems.

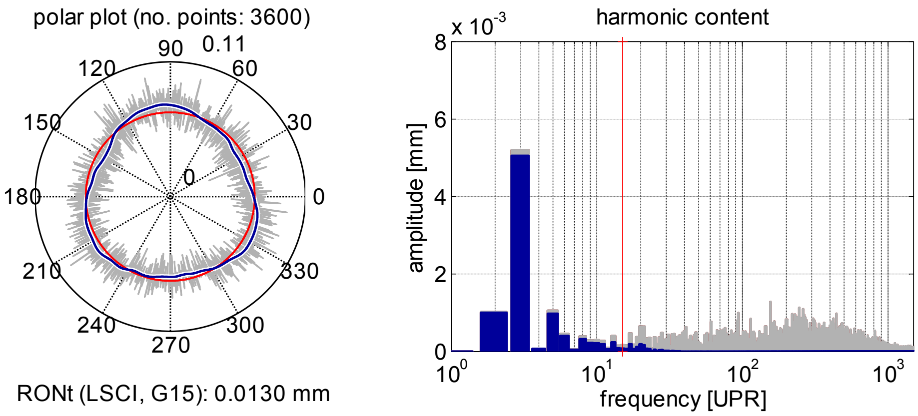

Figure 5. Profile obtained with the CT-system using Setup #1. Extracted circumferential line (grey), roundness profile (blue), associated circle (red).

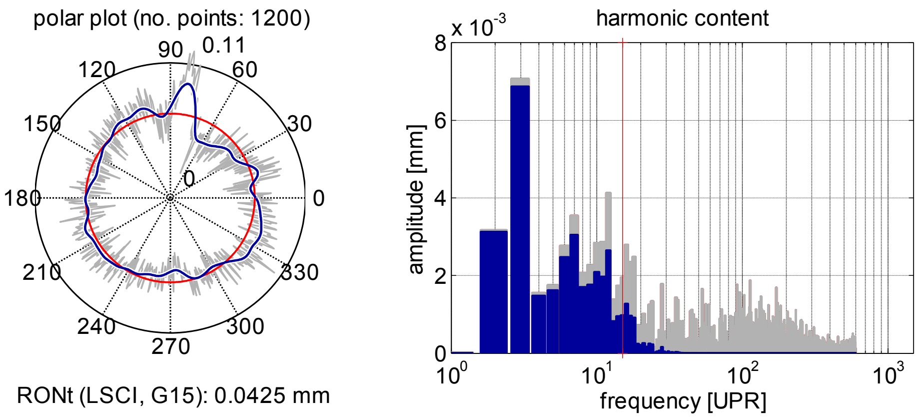

Figure 6. Profile obtained with the CT-system using Setup #2. Extracted circumferential line (grey), roundness profile (blue) and associated circle (red).

One of the extracted circumferential lines obtained with the Setup #2 is shown in Figure 6. By analysing this profile, other effects (besides the noise presented in Setup #1) can be observed: a local deviation near 80° degrees, and the occurrence (or increasing) of aliasing. The aliasing can be observed by the enlarged amplitudes of harmonics above 20 UPR, and by the sudden cut at the sampling frequency (1200 UPR). More important, however, is the occurrence of the local deviation: the extracted profile suffers a severe distortion, bearing little resemblance to the reference profile. This explains the large differences between MCCI diameters and RONt values (even for the filtered profile) presented by the Setup #2.

3.2. Analysis of the sampling interval on the "virtual probing"

The circumferential lines extracted from one virtual surface using different sampling intervals are shown in Figure 7. It can be seen that the profile extracted with 105 points is severally disturbed by aliasing, which can be observed by comparing its harmonic content with the harmonic content of the 3600 points profile (see Figure 5). The influence of aliasing on geometrical evaluations is evidenced by comparing the Diameter (MCCI, G15) values. The diameter of the profile with 105 points resulted larger than the diameter of the 3600 points profile, when the last one should be equal or greater than the first one.

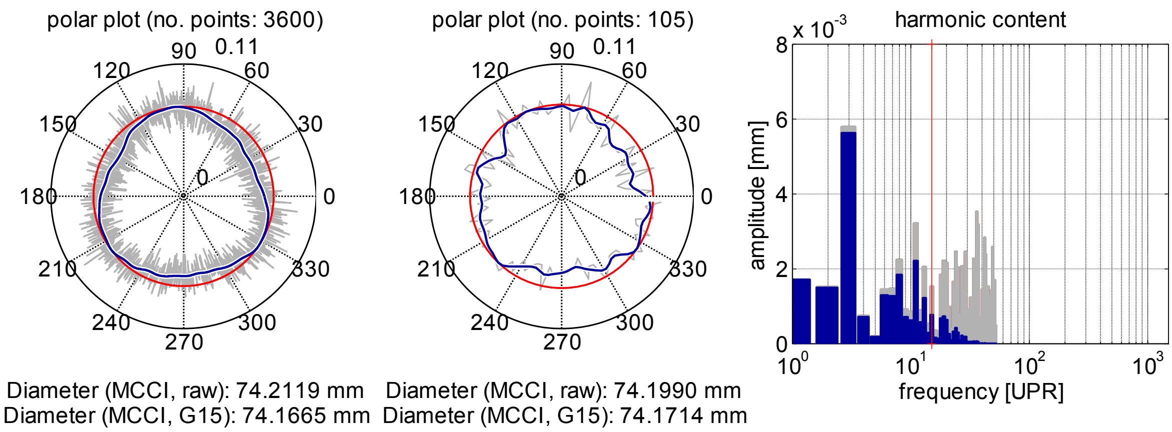

Figure 7. Profiles obtained with the CT-system using Setup #1, resampled with 3600 points (same profile from Figure 5, left) and with 105 points (polar plot, center; harmonic content, right).

4. Discussions and concluding remarks

The use of the experimental approach described on this paper showed to be useful in gaining knowledge on the extraction operation performed by CT-systems. By the results of the presented experiments, it was possible observe the occurrence of aliasing depending on the number of voxels used to define the extracted features. Even though the voxel size was intentionally varied in the two CT setups, this conclusion can be extrapolated to parts that have features sampled by a small number of voxels. In this sense, the analysis of the extracted integral features can be considered as a method to indirectly evaluate the quality of the voxel matrix (given a fixed thresholding operation). The occurrence of aliasing was also observed at the virtual extraction. This suggests that the maximum possible number of points should be used on the sampling strategy.

The influence of the above mentioned (and other) effects on the accuracy of geometrical evaluations was investigated by comparing numerical results and characteristics of integral extracted features. However, using only numerical results to analyse CT measurements may lead to misleading conclusions. For instance, the observed LSCI diameter values obtained with the completely distorted profile of Setup #2 resulted closer to the CMM values than those obtained with Setup #1. These results do not discourage the use of numerical results, but highlight the relevance of also analysing the extracted integral features.

As seen by the results, the influence of extraction distortions will be more severe for specifications operators requiring association/ evaluation operations based on functional extremes (e.g. diameter calculated with MCCI method; RONt evaluation). The use of simplified verification operators (e.g. using a least squares circle when the specification requires using the maximum circumscribed circle, or filtering with lower cut-off frequencies than the specified) to minimize the effects of these distortions can be called into question. On one hand, this decision may reduce the uncertainty introduced by the CT-system during the extraction operation; on the other hand, it will introduce method uncertainty on measurement results (e.g. frequencies of functional interest removed by mistakenly filtering the extracted profile).

Eventually, the uncertainty introduced by the CT-system may be significantly reduced at the cost of slightly increasing the method uncertainty. For instance, the difference between Diameter (LSCI, raw) and Diameter (MCCI, raw) observed on the reference measurements is much lower than the difference between CMM and CT Setup #1 on evaluating the Diameter (MCCI, raw). The same comparison is valid for the use of filtering to reduce the influence of noise. In any case, the use of simplified verification operators must be carefully analysed, otherwise the measurement uncertainty may result unacceptably high.

Finally, the combined use of systematic experiments and analysis of integral extracted features showed to be a useful tool for the CT user in selecting the measurement parameters for geometrical evaluations, and even to decide whether a CT-system is suitable for performing a given measurement task.

Acknowledgments

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