Assessment of the single point uncertainty of dimensional CT measurements

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Abstract
A method analysing the local variations of a series of CT measurements to determine the single point noise is presented. Using a realistic simulation model of the CT system, the mean local offset and the single point uncertainty can additionally be estimated. The method is tested on a measurement series of a micropart. It is shown that the method is capable of identifying areas of increased uncertainty caused by artefacts and of quantifying the value of the single point uncertainty. Additionally, the method is validated using an existing method that is capable of assessing the local quality of a CT measurement.

Keywords: computed tomography, dimensional metrology, single point noise, systematic offset, single point uncertainty, uncertainty mapping, error sources, simulation, artefacts

1 Introduction

During the last decade, X-ray computed tomography (CT), a technology that differs considerably from classical, tactile coordinate measuring machines (CMMs), has become more and more accepted in dimensional metrology. Instead of probing a comparably small number of surface points, CT non-destructively measures the whole surface of a part (including complex and internal features) simultaneously with a high point density. While the uncertainty of a single measured surface point is usually significantly smaller for a tactile CMM, CT (partially) compensates for this by using the statistical advantage of the large number of surface points available when associating standard geometries with these points.

Repeated CT measurements of the same part, even if exactly the same acquisition parameters are used, will not give the same results. Therefore, when a surface point at a specific position of the part is extracted, the position of this extracted point will not only deviate from the real surface of the part, but also slightly vary for each different measurement (in particular in the presence of artefacts). This is visualised in Figure 1: Four CT scans of the same object result in four different surface datasets (green, blue, red and cyan; the nominal surface of the object is depicted in white). Within this paper, the single point noise is defined as the standard deviation of a repeated measured surface point in direction of the nominal surface normal at this point (see Figure 2). The single point noise and the mean systematic offset to the real surface of the part both contribute to the single point uncertainty.

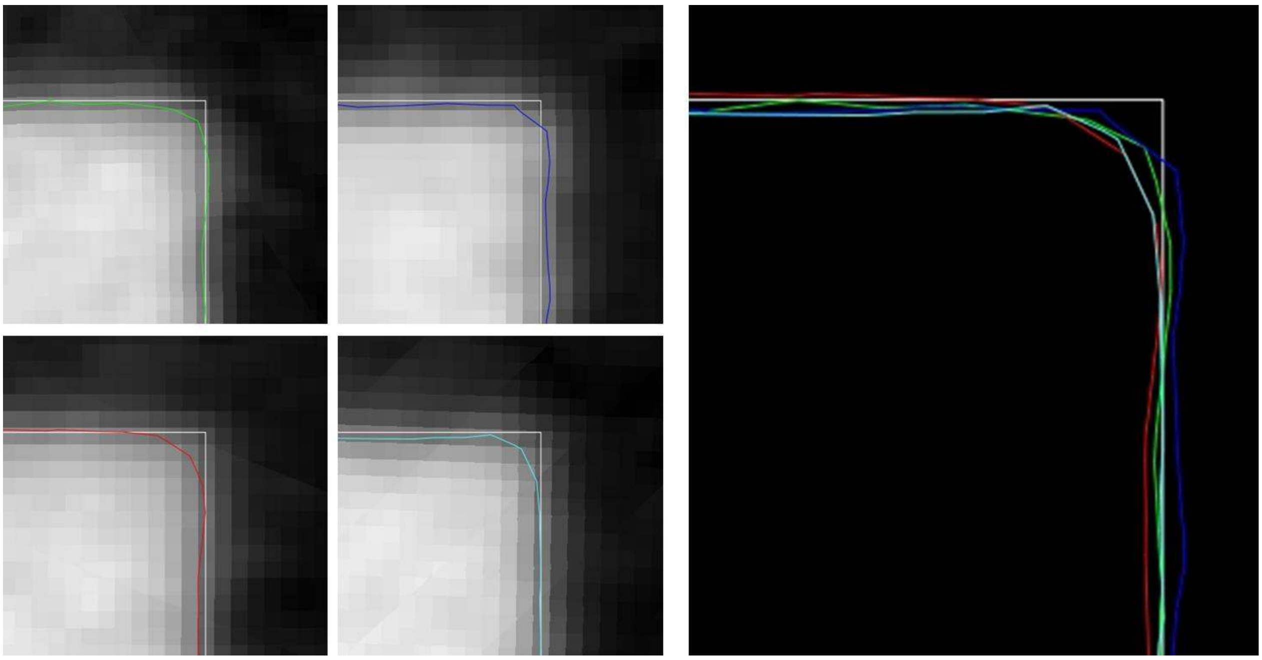

Figure 1: Magnified visualisation of four different scans of the same object including the extracted surfaces (green, blue, red and cyan) and the nominal surface (white). On the right side, the four surfaces are depicted in one image, illustrating the local variations of the extracted surfaces.

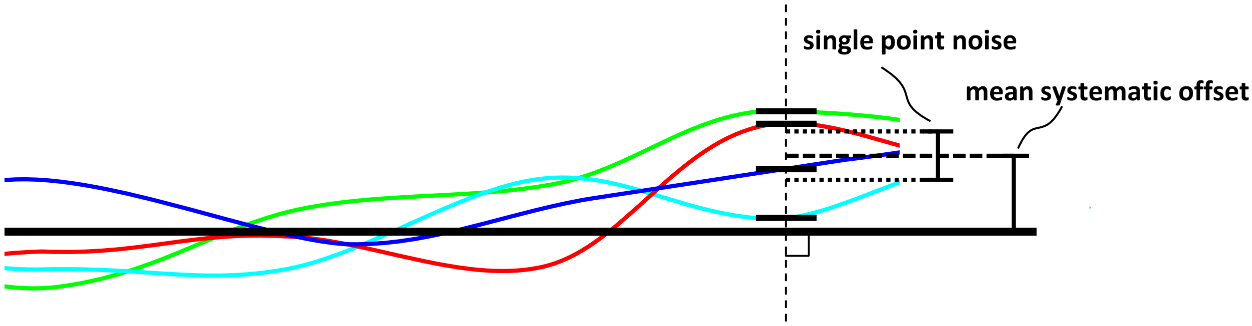

Figure 2: Exemplary calculation of the single point noise and the mean systematic offset for the extracted surface datasets of four different (simulated) measurements of the same object. The single point noise is defined as the standard deviation of a repeated measured surface point in direction of the nominal surface normal at this point. The mean systematic offset is the average of the perpendicular distances.

For a correct interpretation of measurement results, knowledge about the reliability of the results is crucial. This applies in particular for CT, as the quality of a measurement strongly depends on a large variety of different influencing variables (e.g. material and orientation of the part or acquisition parameters). For this reason, a broad range of methods are being used for an objective assessment of the quality of a measurement:

- If a reference measurement with low measurement uncertainty is available, it is possible to evaluate typical measurement deviations [1].
- A more sophisticated and laborious approach is to determine the measurement uncertainty. For this purpose, different methods are possible, e.g. using calibrated workpieces [2], [3], the numerical uncertainty determination [4], [5], [6], [7], [8], or an uncertainty budget [9].
- To avoid the efforts of a reference measurement or a measurement uncertainty determination, methods have been developed to assess the quality of a measurement by evaluating the raw data, e.g. by analysing the distribution [10] or the Shannon Entropy [11] of the grey values. The result is a (global) parameter that is assigned to a measurement to describe its quality.
- As the quality of a CT measurement may vary locally (e.g. in the presence of artefacts or due to different penetration lengths), several methods try to assign local quality parameters, e.g. by carrying out a Bayesian analysis [12] or by analysing the grey values in the proximity of a surface point [13], [14], [15], [16].

For CT, dimensional measurements are carried out by associating standard geometries (usually by the total least square method) with a partitioned surface dataset. For this reason, the single point noise and uncertainty have a large influence on the measurement uncertainty of the final measurement results. As different error sources (e.g. noise, misalignments of the components, beam hardening or scattered radiation) and the resulting data artefacts may impact different regions of a CT measurement with different magnitude, the single point noise and uncertainty also fluctuate locally. Knowledge about these properties may therefore be a helpful tool for a locally resolved assessment of the quality of a dimensional CT measurement.
The local single point noise and uncertainty of surface datasets have been addressed in different publications:

- Schmitt et al. [17] and Krämer et al. [18] added synthetic noise to CT surface data to investigate the impact of the single point noise on the final measurement results.
- Lifton et al. [19] investigated the impact of noise in the volume data on the uncertainty of the extracted surface.
- Outside dimensional metrology with CT, Pauly et al. [20] described a method to assess the local uncertainty of a surface calculated from a finite number of surface points, while Grigoryan et al. [21] investigated methods to visualise the surface uncertainty.

2 Method

Data foundation of the method is a series of (in this study: 20) measurements respectively simulated measurements of the same part under repeatability condition. To calculate the single point noise, the mean systematic offset and the single point uncertainty, a strongly refined version of a nominal/actual comparison is carried out. The following steps have been implemented in MATLAB:

1. Basis of the analysis is the nominal geometry of the part (CAD file) formatted as STL. In the whole algorithm, the centres of the triangles of STL are used as sampling grid of the analysis. As CAD programs usually generate STL files with varying triangle size (larger triangles for flat surfaces and smaller triangles for small curvatures), the STL file is modified in the first step: Large triangles of the file are divided along their largest edge iteratively, until all edges of the STL file are shorter than a defined threshold (in this study: 100 µm). This way, an adequate sampling density is ensured without changing the geometry of the STL file.
2. The surface datasets of the measurements (as well in the STL format) are imported. To generate the STLs files, the volume data of each measurement is initially imported in VG Studio MAX. Using reference geometries measured on the part, the datasets are transformed from the machine coordinate system into the workpiece coordinate system.

This ensures that all datasets are aligned in the coordinate system of the CAD file that is used a reference. The advanced surface determination (point density preset 'normal') is then used to export the surface datasets to the required STL files.
3. Using an efficient implementation of a ray tracing algorithm, for each triangle of the CAD file a ray (originating in the centre of the triangle and perpendicular to the surface) is generated and the positions of the closest intersection with the measured surfaces are calculated (see Figure 2). For 20 measurements, this results in 20 local deviations for each triangle of the CAD file.

For **real measurements**, the following steps are carried out:
4. Using the result from step 3, the local single point noise is determined for each triangle of the CAD file by calculating the standard deviation of the local deviations.
5. The single point noise is depicted as a colour-coded visualisation.

The single point noise can be used to assess the quality of a measurement: for a series of ideal measurements, each measurement should result in the same surface dataset, yielding a single point noise of zero. However, a reduced overall quality of a measurement series induces unwanted variations of the extracted surfaces, consequently causing an increased single point noise (in particular for areas affected by data artefacts).

For **simulated measurements**, a more extensive evaluation is possible:
4. Additionally to determining the single point noise for each triangle of the CAD file, the mean systematic offset (average of the local deviations) can be calculated. This allows an estimation of the local single point uncertainty with a coverage factor k:

$$\text{single point uncertainty} = k \cdot \sqrt{(\text{single point noise})^2 + (\text{mean systematic offset})^2}$$

5. The single point noise, mean systematic offset and the single point uncertainty are depicted as colour-coded visualisations.

As the nominal geometry (CAD file) of the part is used as input for the simulation, all detected systematic offsets from this geometry must originate from the simulated measurement process. This is not the case for real measurements, as here the systematic offset comprises two effects, which are difficult to separate: fabrications artefacts (differences between the CAD file and the real geometry of the part) and imperfections of the measurements process. Therefore, only for simulated measurements, the mean systematic offset (and subsequently the single point uncertainty) allows a more detailed analysis of the quality of the measurement process.
Decisive for the significance of the information yielded from simulated measurements is the degree of reality of the simulation tool used. For this study, the virtual metrological CT (VMCT, currently under development within the EMRP project microparts - 'Multi-sensor metrology for microparts in innovative industrial products') is used [6], [7], [8]. The VMCT uses the software tool 'aRTist' (**a**nalytical **R**adiographic **T**esting **i**nspection **s**imulation **t**ool) [22] by BAM (Federal Institute for Materials Research and Testing, Germany) to model the CT system (Werth TomoCheck 200 3D) at the Institute of Manufacturing Metrology as realistically as possible. As the aim of the VMCT is to facilitate the numerical uncertainty determination for a metrological CT, all significant error sources for dimensional measurements of microparts (e.g. size, form and drift of the focal X-ray spot, polychromatic X-ray spectrum, misalignments of the detector and rotational stage, noise and unsharpness of the detector) are included in the VMCT, ensuring simulation results very close to real measurements [8].

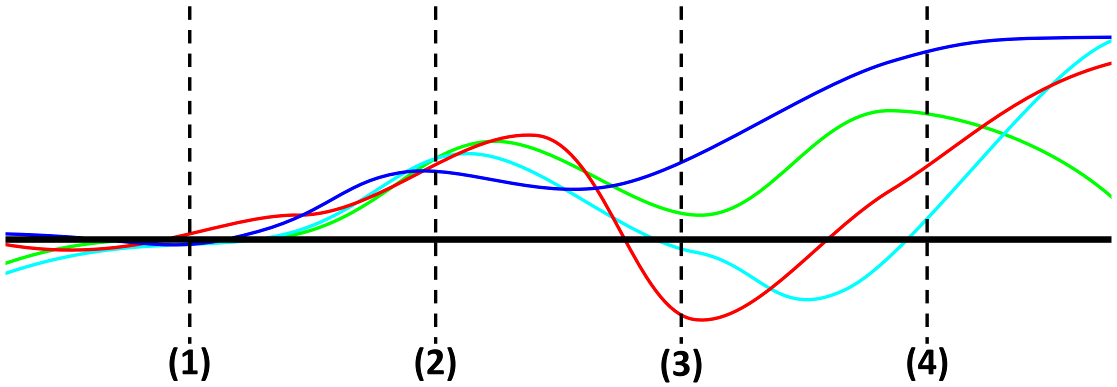

Figure 3: Schematic visualisation of four different results of the analysis with varying single point noise and mean systematic offsets.

For a single analysed point, four basic types are possible as a result (schematically visualised in Figure 3):
(1) Low single point noise and low mean systematic offset: this is the ideal case, resulting in a low single point uncertainty.

(2) Low single point noise and large mean systematic offset: the individual measurements show the same constant offset, resulting in an increased single point uncertainty.
(3) Large single point noise and low mean systematic offset: the individual measurements result in different local deviations, but on average there is no systematic deviation. This also results in an increased single point uncertainty.
(4) Large single point noise and large systematic offset. For this case, the single point uncertainty is largest.

3 Results

The method was tested on a connector piece by LEGO System A/S (Denmark), one of the workpiece-like reference standards of the microparts project. The material of the connector itself is polycarbonate. As depicted in Figure 4, the connector is attached to a central rod (acrylonitrile butadiene styrene) and fixed in a 3D-printed structure (polyoxymethylene). As it is planned to use the connector as a reference standard close to production, purpose of the fixture is to protect the calibrated connector from damage while still allowing tactile and optical measurements.

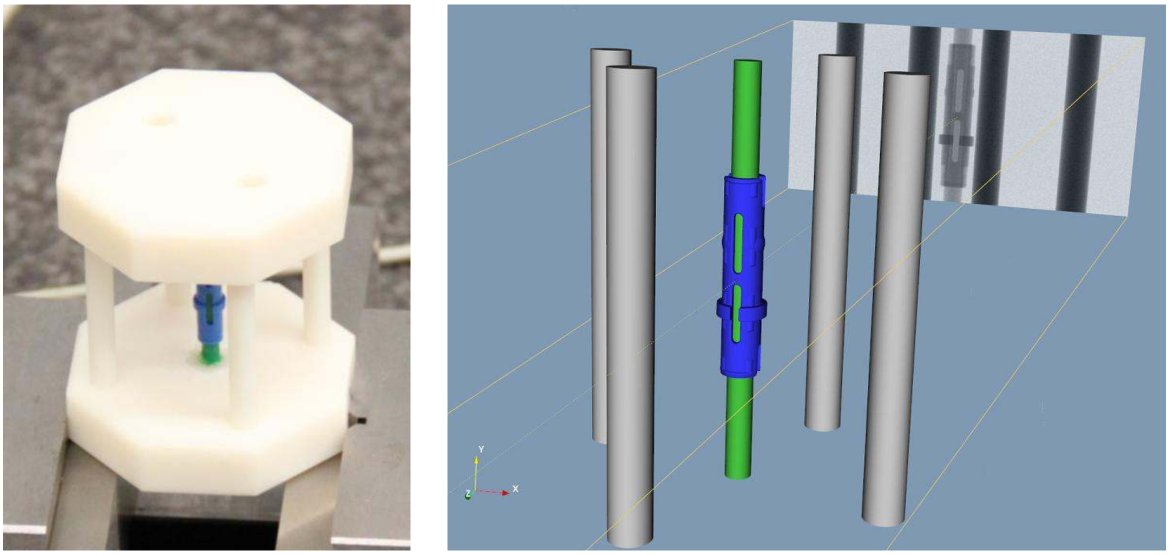

Figure 4: LEGO connector including fixture. The 3D-printed fixture is designed to protect the calibrated connector from damage while still allowing tactile and optical measurements. The right side shows the aRTist scene of the simulation.

For this study, 20 real measurements (Werth TomoCheck 200 3D, voxel size 30 µm, 70 kV acceleration voltage, 300 µA tube current, 1600 projections, integration time 1500 ms), and 20 simulated measurements (VMCT, modelling the real measurement as realistically as possible) of the connector were evaluated using the novel method. Due to the size of the fixture, no smaller voxel sizes than 30 µm were attainable. Furthermore, the outer cylinders of the fixture induce streak artefacts. As it is depicted in Figure 5, the streaks affect the connector directly. Further information about the measurements of the connector and a more detailed description of the simulation (including a numerical measurements uncertainty determination) can be found in [8].

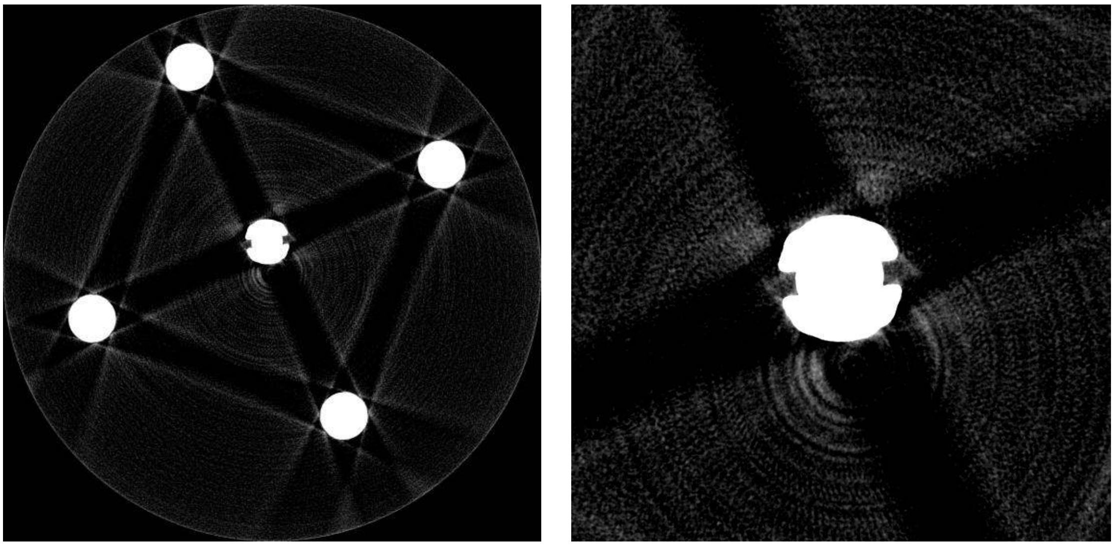

Figure 5: Typical cross-section of a measurement (note that brightness and contrast of images have been heavily adjusted to reveal artefacts). In the magnified visualisation (right), streak artefacts (induced by the fixture) affecting the connector are visible.

The single point noise is visualised in Figure 6 (top: real measurement; bottom: simulated measurement). Extent and distribution of the single point noise are similar for real and simulated measurements. For the most part, the surface is measured with a comparably small single point noise of typically 2 µm to 4 µm. However, regions in the proximity of sharp edges and small curvatures and regions affected by streak artefacts exhibit an increased single point noise in the magnitude of 8 µm and more.

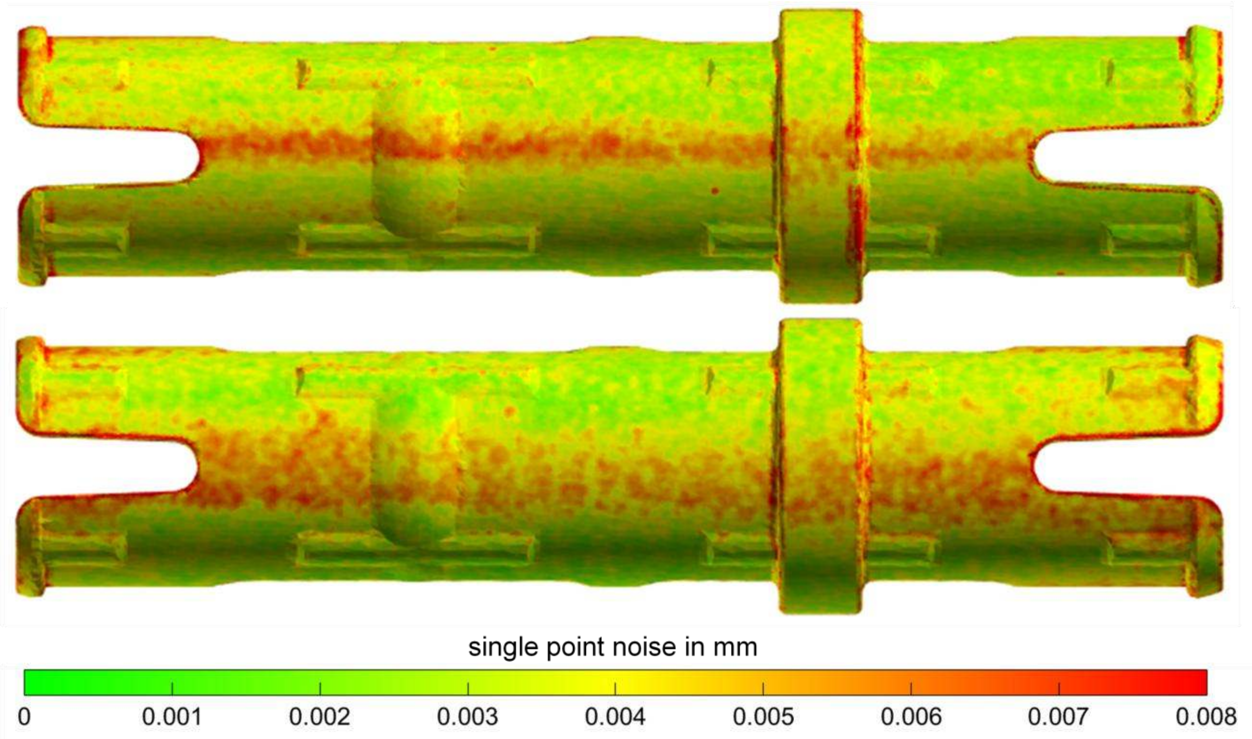

Figure 6: Single point noise of the real (top) and simulated measurements (bottom).

For the simulated datasets, the mean systematic offset of the measurement can be calculated (see Figure 7). Two significant effects are observable:

- Due to the limited structural resolution of CT, sharp edges and small curvatures are rounded off, leading to a negative systematic offset. The absolute value of the offset increases for smaller curvature radii.
- The streak artefacts induce a positive local offset of approx. 20 µm.

It is remarkable that regions with increased single point noise and increased mean systematic offset coincide.

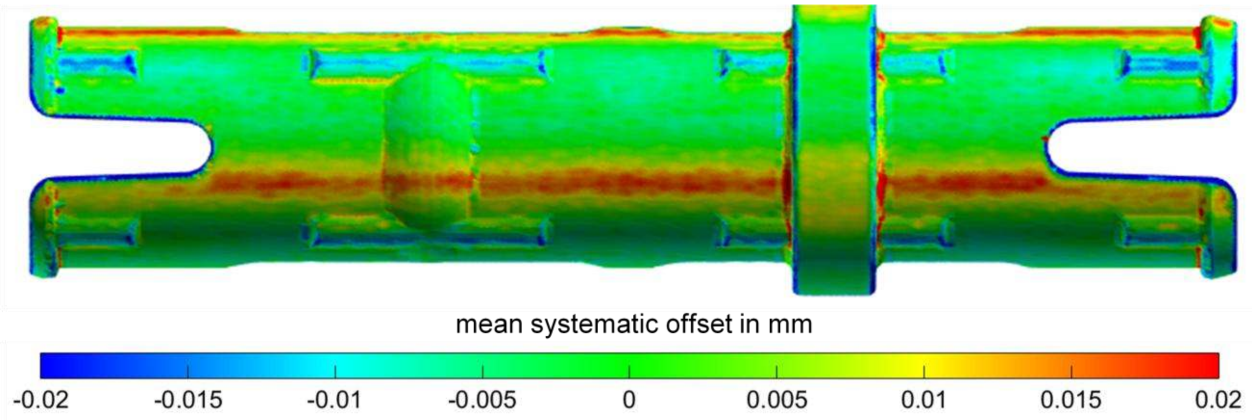

Figure 7: Mean systematic offset of the series of simulated measurements.

The estimated single point uncertainty (k=2) of the measurement (uncertainty map), calculated from the single point noise and mean systematic offset, is visualised in Figure 8. As the main contributor is the mean systematic offset, it is again noticeable that (due to the limited structural resolution) small geometries can only be measured with an decreased accuracy. The same applies to regions affected by the streak artefacts.

When interpreting the estimated single point uncertainty, it should be kept in mind that there might be discrepancies between the simulation and the real measurement. For the case of the connector, the results from [8] suggest that the simulation overestimates the effect of the artefacts on the final measurement results to a certain extent.

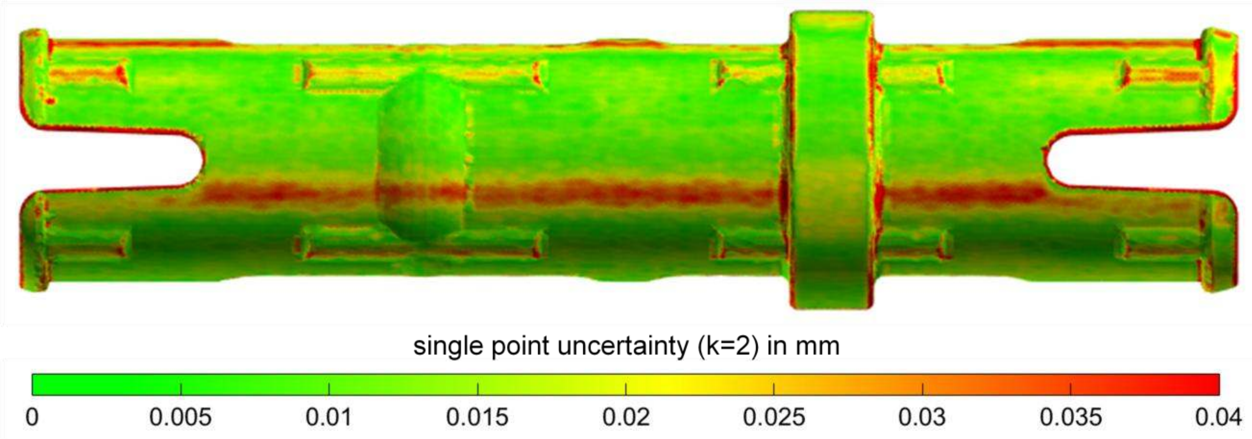

Figure 8: Estimated single point uncertainty of the simulated measurements, calculated from the single point uncertainty and the mean systematic offset (uncertainty map).

Nevertheless, the analysis of the single point uncertainty yields helpful information to minimise the measurement uncertainty for future measurements by optimising the fixture of the reference standard:

- To reduce the impact of the streak artefacts, the positions of the cylinders of the fixture should be changed in such a way, that the streak artefacts connecting these cylinders do not influence the part itself. Furthermore, as the X-ray absorption of polyoxymethylene (fixture) is significantly larger compared to polycarbonate (connector), it should be investigated if it is possible to use a lighter material for the manufacturing of the fixture.
- To reduce the single point uncertainty for small geometries, it is advisable to position the cylinders of the fixture closer to the part. This allows a larger geometric magnification, therefore improving the structural resolution of the measurement.

Using this information and keeping in mind the intention of the fixture (protecting the workpiece-like reference standard from damage while allowing tactile and optical measurements), an appropriate optimised design of the fixture can be developed within the microparts project.

4 Comparison with existing method

For verification of the results, they are compared to an existing method to assess the local quality of a CT measurement, described in more detail in [13], [15]. This method analyses the grey values in the proximity of the extracted surface dataset of a real or simulated measurement. The underlying idea of the analysis is that for a surface point with high accuracy, high quality and artefact-free grey values (noise-free, with a sharp and symmetric transition from low to high grey values) are preferable, as the surface extraction yields the most accurate results in this case. Deviations from these ideal characteristics are detected and assumed as decreasing the accuracy of the surface point investigated. Using this analysis, a local quality value (LQV) can be assigned to each extracted surface point of the measurement.

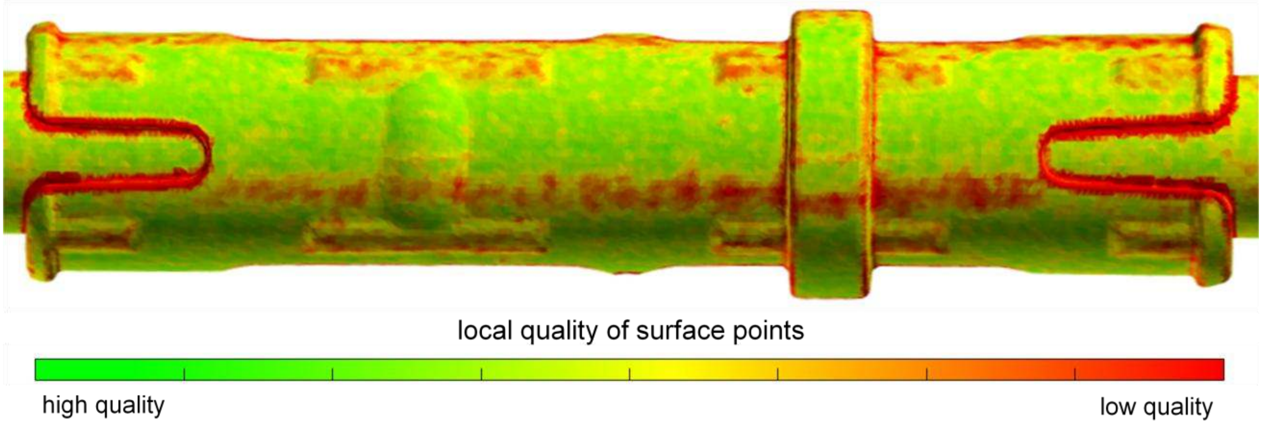

Figure 9: Colour-coded visualisation of the local quality value (LQV) for a single real measurement of the connector to verify the single point uncertainty. The quality values are calculated by analysing the symmetry and homogeneity of the grey values in the proximity of the extracted surface points. A good agreement to the simulated single point uncertainty (Figure 8) is evident.

A variety of different algorithms can be used to analyse the grey values. For the analysis in this paper, the symmetry of the transition from low to high grey values along the normal vector and the homogeneity of the grey values perpendicular to the normal vector of the surface are assessed. As no more than the extracted surface dataset and the volume data of a single

measurement are necessary to calculate the LQV, no reference measurement and no repeated measurements are required to carry out the analysis. The results (the estimated quality of the extracted surface points) are illustrated using a colour-coded visualisation of the measured surface.
One of the real measurements of the connector was analysed using this method, the results are depicted in Figure 9. The distribution of surface point of low quality is similar the points of increased single point uncertainty from Figure 8. It can be concluded that surface points of reduced accuracy are detected reliably by both methods.

5 Conclusion

A method to determine the single point noise (for real and simulated measurements) and mean systematic offset and single point uncertainty (for simulated measurements) was presented. To maximise the validity of the simulated results, a realistic simulation model (VMCT) of the real CT system was used. To verify the novel method and the simulation used, a comparison with an already existing method to determine the local quality of a measurement was carried out. A good agreement of the results is observable.
The method is a strongly refined version of the nominal/actual comparison that is already in broad use for industrial CT. While it is also possible to investigate local systematic offsets by carrying out a conventional nominal/actual comparison for a single realistic simulation, the presented method delivers more stable results as a large number of simulations are taken into account. The single point noise and single point uncertainty, however, can only be determined using the refined version.
In combination with a realistic simulation tool, the method is capable of using the single point uncertainty to describe the local accuracy of a CT measurement. While an increased effort is linked to this method as it is necessary to evaluate a larger number of measurements, there is a significant advantage compared to other methods assessing the local quality: result of the analysis is a clearly specified value (in mm) for the local single point uncertainty. The method can therefore be used to verify and/or enhance other methods that determine the local quality of a CT measurement.
Within the microparts project, the method is already in use to verify the VMCT (by comparing characteristics of the surface datasets from real and simulated measurements) and as a tool to gain new insights on the origin of the uncertainty of a measurement. The knowledge gained from this can for instance be used to optimise the measurement process, as it was demonstrated for the fixture of the connector.
As a comparably large number of real or simulated measurements are required to carry out the analysis, the method is rather time-consuming. It is therefore primarily relevant for research and developers of CT system, for example to gain a deeper understanding of the measurement uncertainty. For the industrial end user, the method seems most suitable for the analysis of larger measurement series or inline measurements, so that the information gained is worth the effort (furthermore, in these cases the required datasets are already available without the need for any additional measurements). However, for a more detailed analysis, it should be kept in mind that an experienced expert is needed for the correct interpretation of the results and that the accuracy of the simulated results strongly depends on the simulated model of the CT system.

6 Outlook

As already mentioned, it is necessary to transform the various datasets from the machine coordinate system into the same workpiece coordinate system. In this paper, reference objects were measured on the datasets to carry out the registration, but it is also possible to use the best fit algorithm to align the measurements to the CAD model. One way or another, variations of the alignment of the part might be misinterpreted as a variation of the geometry of the part's surface itself and therefore distort the single point noise. First basic investigations suggest that this effect is detectable, but small compared to the single point noise induced by artefacts. However, more detailed investigations are required.
When carrying out dimensional measurements on CT datasets, usually the final measurement results are calculated taking a large number of surface points into account. Therefore, further investigation about the propagation of the single point uncertainty (consisting of single point noise and a systematic offset) to the final measurement uncertainty are needed.
Finally, it should be mentioned that the method is not only restricted to CT. As input data, only a series of measurements and the nominal geometry are required, while the source of the measurement data is irrelevant. Therefore, it is also thinkable to analyse measurements of other sensors for areal measurements (e.g. fringe projection systems or even surface measurements using white light interferometry) with help of the presented method.

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