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NUMERICAL MEASUREMENT UNCERTAINTY DETERMINATION FOR COMPUTED TOMOGRAHPY IN DIMENSIONAL METROLOGY

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Abstract – In Computed Tomography (CT) in dimensional metrology, the numerous complex measurement process steps with various influences present a significant impact on the measurement results. For the determination of measurement uncertainty, it is therefore important to consider all of these influences. The paper discusses the possibilities of a promising approach, the numerical uncertainty determination for CT in dimensional metrology.

Keywords: computed tomography, dimensional metrology, standardization, numerical uncertainty determination, simulation

1. NORMATIVE REFERENCES AND GUIDELINES

According to VDI/VDE 2617 part 8 [1], several procedures are thinkable for task specific uncertainty determination regarding coordinate measuring machines (CMMs) with Computed Tomography (CT) sensors:

First, using the analytic approach given by the first part of the “Guide to the expression of uncertainty in measurement” (GUM or JCGM 100 [2]) seems hardly feasible, in consideration of the complex nature of the entire measurement process.

Second, the determination of measurement uncertainty with use of calibrated workpieces (according to ISO 15530-3:2011 [3]) is applicable for CT and is described in more detail in the new guideline VDI/VDE 2630 part 2.1 [4], however a similar calibrated workpiece is required and the procedure is very time-consuming.

And third, it is possible to determine the measurement uncertainty by simulation (GUM Supplement 1 or JCGM 101 [5]). This is topic of the recent research and of this paper, cause it seems to be the most promising and universal approach.

For tactile CMMs, the numerical uncertainty determination via VCMM (virtual coordinate measuring machine) is already in use in accredited laboratories [6]. For X-ray CT, first investigations have been carried out by Hiller et al. [7]. It has been shown that, basically, it is possible to determine the measurement uncertainty by simulation. However, there is still a lack of researches regarding CT systems that are dedicated for dimensional metrology and therefore make higher claims against the accuracy compared to conventional CT systems for material testing.

A detailed, more fundamental description about numerical uncertainty determination using the Monte Carlo method can be found in [5].

In guideline VDI/VDE 2617 part 7, the basics of numerical uncertainty determination for dimensional measurements are described [8]. Although the guideline focuses on tactile measurements, most of its content can be transferred to X-ray CT. By reason of the complex measurement process steps additional points compared to the VCMM inputs must be considered.

2. NUMERICAL UNCERTAINTY DETERMINATION

Basic idea of numerical uncertainty determination is to model the whole measurement process in a simulation tool. Instead of carrying out real measurements and determining the measurement uncertainty from a statistical evaluation of the measurement results, the simulation tool is used to generate the measurement results.

For a correct determination of measurement uncertainty, the whole measurement process (including data acquisition and data evaluation) needs to be considered. There are several basic requirements to carry out a numerical uncertainty determination for CT: a virtual model of the part to be measured (usually in the STL file format), knowledge about the material composition of the part and a precisely defined measurement task (according to the geometrical product specification standards).

Furthermore, a simulation tool is needed that is capable of reproducing real X-ray CT measurements realistically.

To analyse dimensional measurements for simulated and real data sets, the same measuring software is used as for real measurements.

As the whole process is complex, an experienced operator is required for realistic simulation results. The operator needs thereby a deep knowledge about the characteristics of all quantities that have a significant influence on the measurement results.

Additionally, as it is very time-consuming to perform the large number of simulations, a high computing power is needed.

2.1. Procedure for determination by simulation

To determine the measurement uncertainty numerically, several measurements are simulated, resulting in projection datasets similar to real measurements. Using the same algorithms (e.g. reconstruction, surface determination, definition of the coordinate system, filtration of the surface data and association of geometric elements) that are used for the real measurement data, the simulated measurement results are being evaluated. By a statistical analysis of the measurement results of the simulations, the expected measurement uncertainty can be estimated. Fig. 1 shows the principle process of the numerical uncertainty determination.

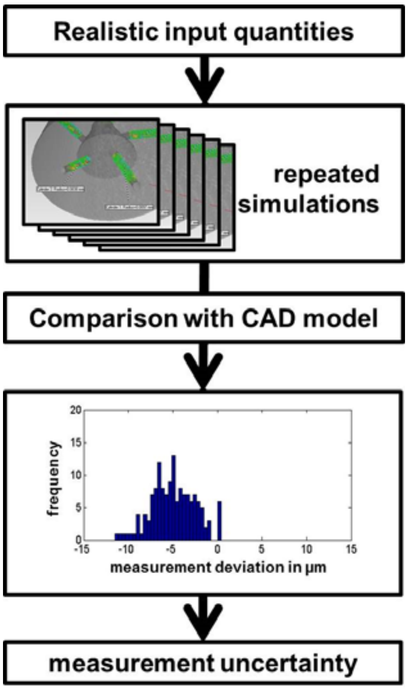

Fig. 1. Principle numerical uncertainty determination. Measurement uncertainty derived from statistical evaluation of the simulation results

To achieve a realistic and robust estimation of the measurement uncertainty, the number of simulations carried out, must be as large as reasonably possible. In [5], the number of 100,000 simulations is proposed, but it is also stated, that the number has to be reduced drastically, if the simulation is complicated and very time consuming (which is obviously the case for CT). For these cases, a number of 50 to 100 is considered to be sufficient. For these small numbers of simulations, a Gaussian PDF would be assumed for the calculation of the coverage interval from the simulated measurement results. In [8], no specific number of repetitions of the simulation is mentioned. In [7], 50 simulations were used to estimate the uncertainty.

To achieve realistic results, it has to be ensured that the results of a single simulation realistically resemble real measurements. Therefore, the simulation has to be adjusted to the respective CT system. For the same reason, the uncertainties and distribution of the input quantities must be estimated realistically and the verification of the whole tool is crucial.

2.2. Error sources

First of all, the input parameters for simulating a virtual CT have to be defined by an experimental method. Such methods deliver a model of a real CT system. For a correct numerical uncertainty determination by simulation, the given CT system needs to include all error sources that induce to measurement deviations.

Typical influences of different error sources that lead to measurement deviations are shown in Table 1. More detailed information about influences is given in VDI/VDE 2630 part 1.2 [9].

Table 1. Typical influences on CT measurement uncertainty.

Error source	Examples for influences
CT device	- X-ray source - kinematic system - detector - …
operator	- maloperation - experience - strategy - …
measurement task	- material - geometry - fixing - …
environment	- humidity - vibrations - temperature - …
Analysis	- reconstruction - BH correction - surface extraction - …

3. ADJUSTMENT OF THE SIMULATION TOOL

This chapter describes the work within the EMRP project “Multi-sensor metrology for microparts in innovative industrial products” that is carried out to adjust the simulation tool aRTist (analytical Radiographic Testing inspection simulation tool) [10] by BAM to the CT system at the Institute of Manufacturing Metrology (Werth TomoCheck 200 3D). We name the resulting numerical model of the CT system a virtual metrological CT (VMCT). For other simulation tools and CT systems, deviating steps might be necessary.

3.1. Basic Geometry

A CT system is based on an X-ray tube, a rotational stage and a detector. For different geometrical magnifications, the distances between these components differ. This is specified by the variables focus detector distance (FDD) and focus object distance (FOD). Additionally, the size of the detector and the size and number of pixels must be known. Obviously, this geometry must be reproduced in the simulation software.

3.2. X-ray tube

aRTist is capable of calculating the spectrum of an X-ray tube. Main input parameters for this are the acceleration voltage, the anode material, the type of the tube (transmission or reflection), the material and the thickness of the prefilter. Additionally, the finite size and form of the X-ray spot must be modelled.

3.3. Physical interactions

To generate the projection images, aRTist calculates the physical interactions between the X-rays and the workpiece. For realistic results, all relevant physical processes have to be taken into consideration.

However, for measurements of microparts, due to the small size of the parts (at the low X-ray energies used, attenuation is dominated by absorption and only few photons are scattered) and the large distance between object and detector (the majority of scattered photons does not hit the detector and forms a smooth distribution), the impact of scattered radiation is negligible. As scattered radiation is modelled by a time consuming Monte Carlo calculation, it is tolerable under these circumstances to skip this calculation step.

3.4. Acquisition parameters

Naturally, the acquisition parameters (acceleration voltage, number of averaged images per projection, number of projections) used in the simulation must comply with the parameters of the real measurement.

3.5. Detector properties

The detector itself has a large impact on the measurement result. As, for different photon spectra, the properties of the detector vary, its properties have to be adjusted for each of the measurement parameter presettings (acceleration voltage, material and thickness of the prefilter). The significant characteristics include:

- Characteristic curve (grey value depending on detected intensity),
- Noise level,
- Detector unsharpness due to internal scatter effects [11],
- Afterglow,
- Procedure of flat field corrections.

3.6. Measured part

To perform a simulation, an accurate CAD file of the part must be imported. The material composition of the part is another input for the simulation. Since the orientation of the part has a large impact on the measurement result, the orientation in the simulation must comply with the orientation the operator uses in the real measurements. As the operator causes variations in the orientation in repeated measurements, this variation must be estimated and included. The same applies to uncorrected thermal expansions of the part during the measurements. This can be done by varying the size of the virtual model of the part during the measurement. Additionally, the fixture holding the part must be modelled in the simulation.

3.7. Geometrical errors

For real CT measurement, to ensure a reconstruction of high quality, the reconstruction requires information about the geometry of the CT system (arrangement of X-ray tube, rotational stage and detector). By calibrating the system setup, misalignments are corrected as far as possible. However, the misalignment will always remain uncorrected to a certain degree. This way, measurement errors are introduced. A simple example is an error in determining the ratio of the FDD and the FOD, resulting in an incorrect calculation of the voxel size. Other misalignments, like a tilt of the detector, induce more complicated artefacts that are hard to detect.

Additional to the initial misalignment, the geometry of the system also changes during the measurement (e.g. drift of X-ray spot). Therefore, for each geometric parameter, an initial offset and a drift over time has to be included to the simulation.

3.8. Unconsidered error sources

Quantities influencing the uncertainty, which are not considered by the simulation, must be estimated otherwise e.g. using expertise. The uncertainty caused by these quantities must be included in the estimated measurement uncertainty. An example for this might be the uncertainty caused by form deviations of the part. In most cases, these are not considered by the simulation, as perfect CAD data are used as input for the simulation.

4. EVALUATION

Within the microparts project, a study was carried out to examine the impact of different error sources on the measurement uncertainty of different geometrical features for typical measurements of microparts by computed tomography. Projection sets of small geometries with high magnification have been simulated and reconstructed to examine the impact of error sources like noise, beam hardening, scatter radiation and X-ray spot size for different magnification factors, materials and penetration lengths.

With the help of the simulation, it is possible to switch error sources on and off separately and therefore examine their distinct influence on different dimensional measurement.

Fig. 2 shows a comparison of a projection image of a virtual part (being used for the study) for ideal settings (no beam hardening, no scattered radiation, no noise, a point X-ray source) with a projection image simulated for realistic settings. It is clearly visible that the realistic projection is of lower quality, as it is noisy, blurry and of decreased contrast.

Additionally, the impact of the error sources on the reconstructed volume datasets (cross sections depicted in Fig. 3) is clearly visible. The ideal dataset is of high quality, while the realistic dataset shows blurry edges, beam hardening and noise. This allows a systematic investigation of the impact of error sources on dataset quality and, subsequently, measurement results.

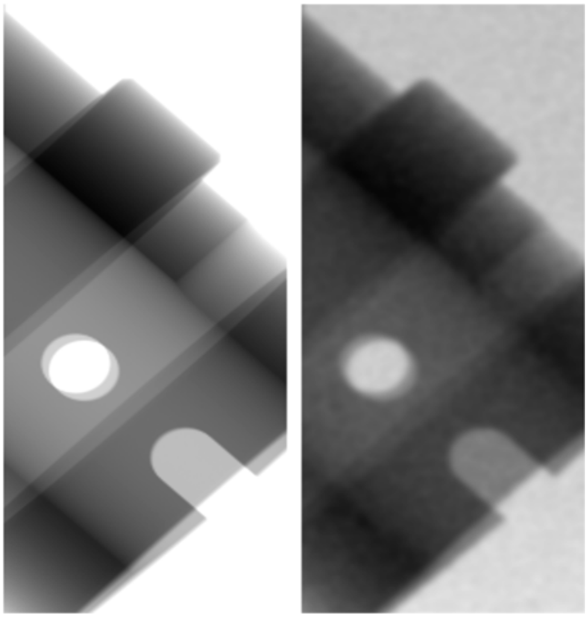

Fig. 2. Comparison of an ideal (left) and a realistic (right) projection.

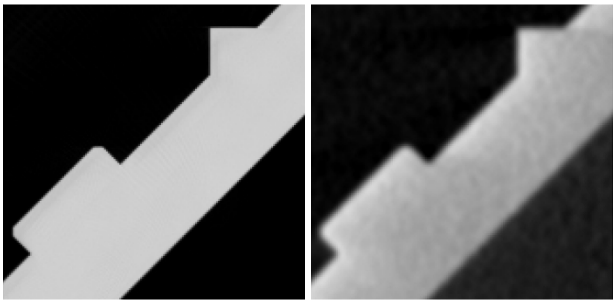

Fig. 3. Comparison of cross section from an ideal (left) and a realistic (right) simulation.

The simulated volumes were evaluated using VGStudio MAX. After defining the local coordinate system, a measurement template is imported and the measurement results exported. For each feature, the result is compared to the nominal value of the CAD data to determine the measurement deviations. For each group of geometrical features (uni-, bidirectional lengths and roundness deviations), the RMS (root mean square) of the measurement deviations is calculated. Thus, systematic and statistical deviations are incorporated, as they both contribute to the RMS. This allows an assessment of the expected measurement deviations. The unidirectional lengths are measured between the centres of two least square circles. Therefore, they are robust against the uncertainty of single surface points and allow the identification of scaling errors. Bidirectional lengths are additionally sensitive to systematic errors of the determination of the surface points, as the two points defining the distance are acquired by virtually probing the surface from two opposite directions. The part bounding surface position depends on the grey values in the proximity of the surface point. Roundness deviations are sensitive to a high uncertainty of single surface points along the circumference.

For the study, in each simulation one error source was switched off. For this, the CT parameters according to Table 2 were used In the case of the ideal measurement all inspected error sources were switched off. The simulation evaluation called standard (see Fig. 4-6) includes all error sources. All of the other parameters of the simulation were adjusted to the characteristics of the CT system at the Institute of Manufacturing Metrology as described above.

Table 2. Adjustments of the CT simulation tool.

Error source	Realistic parameter	Ideal parameter
detector unsharpness	considered	not considered
spectrum	polychromatic (70 kVp)	monochromatic (19 kV, mean energy of polychromatic spectrum)
focal spot size	Gaussian profile diameter of 0.050 mm	Gaussian profile diameter of 0.001 mm
noise in projections	considered	not considered
fixture	included	not included
ring artefacts	considered	not considered

Misalignment and drift effects of the CT's geometry are not being considered in the study for this paper. As this important error source is missing, it is not possible to quantify the absolute values of the expected measurement deviations.

Also additional error sources like voxel size, number of projections, and orientation of workpiece were examined separately and are not part of the results in this paper.

4. RESULTS

Fig. 4-6 show the results of the measurement deviations for each group of geometrical feature and make it possible to estimate the influence of the error sources. The following parameters differ between default and ideal parameters: number of averaged images per projection, detector unsharpness, spectrum, focal spot size, images averaged for flat field correction and the fixture. In each simulation one error source was switched off, except standard and ideal case. Comparing the measurement deviations of the default measurement with the measurement with ideal parameters, it is clearly visible that the expected measurement deviations decrease drastically for the ideal parameters measurement. As expected, the measurement deviations of unidirectional lengths are visibly smaller than those of bidirectional lengths. Due to the (in comparison to other sensors) high uncertainty of a single surface point of a CT measurement, the measurement deviation of a roundness deviation is quite large.

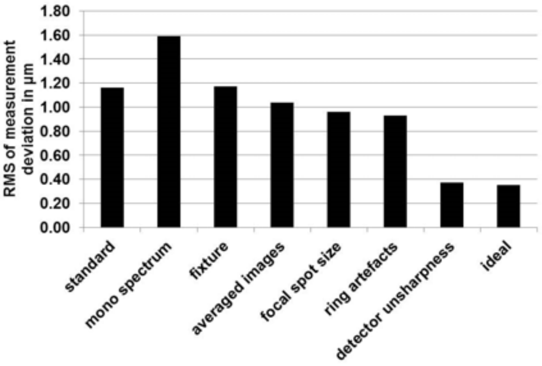

Fig. 4. Influence of error sources on measurements of unidirectional lengths.

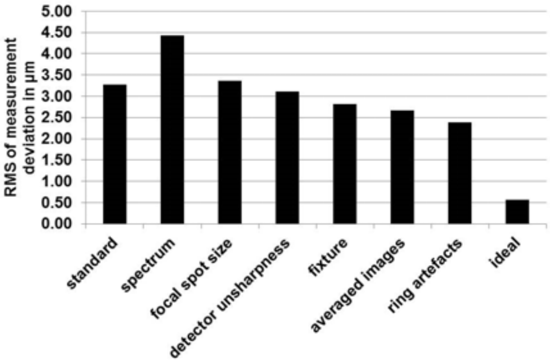

Fig. 5. Influence of error sources on measurements of bidirectional lengths.

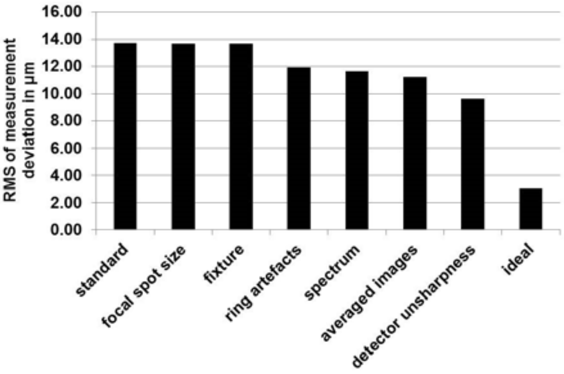

Fig. 6. Influence of error sources on measurements of roundness.

The effect of switching the error sources on and off is best visible when assessing the influence of error sources on measurements of roundness. While a small focal spot has little impact on the measurement of roundness deviations (small decrease of measurement deviation), the comparatively greatest influence on measurement deviations has the deactivated detector unsharpness (largest decrease of measurement deviation).

For this investigation, a noticeable error source for length measurements is the spectrum. Surprisingly, a monochromatic spectrum leads to higher measurement deviations than a polychromatic spectrum. The reason for this is unknown. However, as expected, deactivated error sources in general lead to a reduction of measurement deviations. For unidirectional lengths, neglecting the detector unsharpness causes a strong reduction of measurement deviations. Other error sources seem to be less dominant. In absolute terms, there seems to be no dominant error source in this investigation. However, it has to be stated that these results are only valid for these specific measurement tasks. Other measurement tasks, other workpieces and other CT settings may lead to different results.

5. VERIFICATION OF THE RESULTS

As it is stated in [3], the numerically estimated uncertainty needs to be verified. To do this, it is possible to measure a real calibrated object and compare the experimentally determined measurement uncertainty (determined by repeated measurements) with the results from the numerical uncertainty determination (according to [3]). If the results differ negligible, the numerical uncertainty determination is evaluated as capable of determining the measurement uncertainty for a similar task (e.g. a part comparable regarding material and geometry, with similar features to be measured and similar acquisition parameters of the CT). For a numerical uncertainty determination of an additional measurement task, that deviates from the verification considerably, an additional verification is necessary.

Furthermore, it is advised to verify the compatibility of other properties of the simulated and experimental results. For this, properties like modulation transfer function (MTF), noise power spectrum (NPS), signal-to-noise ratio (SNR) and contrast can be evaluated. However, these properties are calculated from the volume data. For dimensional measurements, the surface determination and the association of geometries are essential. For this reason, the significance of properties that describe the projection and volume data is limited. Therefore, it is advised to carry out investigations on properties derived from the surface data. Examples for this are the local single point uncertainty and the frequency response of the CT system on small surface structures. Naturally, the latter is of great importance for measurements of microparts. A method of investigating the frequency response of a CT system when measuring small geometrical structures based on [12] is explained in [13]. Comparable methods like described in [14] are also applicable. This method based on ascertaining an analogue Gaussian broadening of the measurement system from a deviation between a measured and a calibrated radius. Some information about methods to verify the results of the simulation tool and investigate the consistency of experimental and simulated measurements is also given by [15, 16].

As the characteristics of a CT system can change over time, the verification has to be repeated regularly.

6. CONCLUSION

The investigations of the impact of different error sources on the measurement uncertainty have shown that in absolute terms, it is not clearly identifiable which error source has the largest effect on the results. There are often multiple important error sources, while different error sources have a large impact for different geometrical features.

It has to be stated, that these result specifically apply for the measurement task (CT-system, acquisition parameters, measurement object, geometrical features) examined in this study. For other tasks, the results may vary.

The studies carried out until now have shown, that the numerical uncertainty determination with the aid of a realistic simulation setting is feasible. A comparison of experimentally and numerically determined measurement uncertainty for typical measurement tasks will be presented in the future.

Disadvantages of numerical uncertainty determination are that a large effort is needed to model the CT system and the validity of this approach still needs to be proven. Also numerical uncertainty determination takes a lot of computing time and power.

An advantage is that the task of uncertainty determination is moved away from expensive equipment. Furthermore, uncertainty determination is feasible for internal and hidden geometries without calibration. Conceivable is a predetermination for measurement uncertainty if possible, whereby only the CAD model of the workpiece is needed.

Research at FMT is ongoing, but first results show that it is a promising approach to determine the task specific measurement uncertainty. Especially the decreasing cost of computing power may increase its applicability in the future.

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