Examination of the Measurement Uncertainty on Dimensional Measurements by X-ray Computed Tomography

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Abstract. Computed Tomography (CT) has increasingly been used for dimensional measurements, as is in industrial specimen inspection. Currently the CT is not yet established as a principle of measurement. One requirement for this establishment is the knowledge of the occurring measurement uncertainty, which is indispensable for the comparability and the acceptance of measurement results as well as for decisions based on these results. In CT the measurement process is influenced by the X-ray source, the specimen, the detector, the scanning geometry, the environment, the user, the software and the data evaluation. Therefore there are about 40 input quantities influencing the measurement quantity. An analysis and evaluation of a selection of these input quantities by a simulation-based investigation is presented in the scope of this contribution The dependency of the measurement error and the measurement quality on various influence quantities was investigated systematically.

Introduction

You must measure the things that are measurable, and make measurable the things that are not. This conclusion of Galileo Galilei (1564 - 1642) applies especially to the measurement of geometric quantities by means of computed tomography (CT). Computed tomography with X-rays has become an established technology for the non-destructive detection of defects in industrial quality assurance applications. Lately industrial CT machines are also used for tasks in the field of dimensional control.

Surface-oriented measuring techniques acquire an object as a planar body. Complex internal structures cannot be measured by tactile or optical sensors. As a volume-oriented and non-destructive method, the computed tomography supplies reconstructed data that allows the reproduction of both material properties and the geometric structure of any area of the test object. Generation of components from virtual CAD data is an industrial standard. The conversion of CT reconstructed data to CAD data with the purpose of dimensional monitoring offers a high potential for the product design, but also still requires considerable development efforts.

The results of measurements are the basis of decisions regarding the manufactured products, delivery, reworking or even changes in the manufacturing process of. Therefore the specification of the measurement uncertainty increases the quality of a measurement and is a precondition for comparability and acceptance of CT as a measuring instrument. This paper is outlined as follows: The next section describes the acquisition of the geometric data. In section 2 the evaluation of the measurement uncertainty according to GUM and CT specific problems are presented. Section 3 explains the simulation method used for the investigation of the input quantities, presented in section 4. In the fifth section first results are discussed, the last section gives a short conclusion.

1. Artefacts and Surface Extraction

Dimensional measurements acquire the geometric characteristics of a component and require a highly accurate extraction of the component's surface, i.e. a conversion of the measured CT data into geometric data. The best-known data format is STL (stereo-lithography) which is the basis for the sequenced applications. Many commercial programs expect a threshold as input parameter for the surface extraction. In the ideal case a CT reconstruction supplies noise-free, sharp images that correlate with the density distribution inside the object. Such high-quality images permit the generation of contour gradients for the measuring by means of simple edge finding algorithms.

However, there are various parasitic influences to the X-ray recordings of a component that cause artefacts in the reconstructed 3D volume. Beam hardening (see Source pre-filtration, page 5) and scattering artefacts in real images, for example, cause density gradients which prevent the definition of an optimal threshold for the iso-surface and thus reduce the accuracy of the measures in the CT scan. Even in case of homogeneous material, the definition of a fixed iso-threshold as borderline between material and air is insufficient. An inadequate choice of parameters can result in unwanted effects such as double-layers or holes in the surface.

The Iterative Artefact Reduction (IAR) [1] combines correction methods that improve the quality of 3D CT images by reducing physical parasitic effects. The referenceless calculation of a characteristic curve for beam hardening correction replaces e.g. the time-consuming recording and evaluating of calibration bodies. The Length-Based Scattering Approximation (LBSA) is a simple, but efficient scattered ray model, which considers object forms and supplies comparable results as Monte-Carlo Simulations within a considerably shorter period of time [2].

By using correction methods, the accuracy of nominal/actual value comparisons can be increased into the subvoxel range. The absolute average deviation between the optically digitalized actual value set and CT nominal data is reduced from approx. one voxel in the uncorrected volume to approx. one third of a voxel in the artefact-reduced volume.

2. Evaluation of the Measurement Uncertainty

An important condition for high quality industrial production is the availability of reliable measurements.

One quality feature of a measurement is the evaluation and expression of the measurement uncertainty. According to [3] the uncertainty of measurement is a parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand. A correct statement of the result of a measurement is given by the measurement value and its measurement uncertainty.

The “Guide to the Expression of Uncertainty in Measurement” (GUM) [4]) is considered by ISO as the principal document for the expression of measurement uncertainty:

- worldwide standard for consistent evaluation of measurement uncertainty,
- methodically step-by-step procedure,
- practical and versatile modelling concept,
- based on a solid theoretical foundation.

Uncertainty evaluation in the industrial practice is done by different approaches:

- expression of an uncertainty budget (standard method)
- experimental methods
- theoretical methods (simulation)
- combination of these methods

The standard method to determine the measurement uncertainty according to GUM requires an evaluation model that collects all input quantities influencing the value of the measurand and that qualifies the effects of changes of the input quantity on the measurand. Due to a lack of any self-contained theories for the modelling process, the most complicated part in the determination of the measurement uncertainty according to GUM is to set up the model equation under consideration of all relevant input quantities.

The acquisition of the influence quantities and their interaction could be carried out by experimental measurements also. The key points of the procedure are for example described in [5]. The principle idea is a series of measurements under the same conditions as will also occur in industrial production. Therefore a calibrated workpiece has to be available, similar in size and form to the specimen.

Another elegant alternative is the simulation method. The method is well adapted for very complex measurement tasks. Like in the standard method all influence quantities and their functional dependencies must be known. The evaluation of the measurement uncertainty is then done by a multitude of simulated samples in a virtual experimental set up. The total measurement procedure by the use of a Monte-Carlo based simulation method is described for example in [6].

In the main part of this paper a similar virtual experimental setup with an alternative implementation of the simulation is presented. The task of the presented work is to detect the main influence quantities, thereby serving as a basis for the simulation analysis method described above.

CT specific problems

In computed tomography the evaluation of the measurement uncertainty is complicated by some particularities. The difficulties in dealing with artefacts, which reduce the image quality and complicate the surface extraction, are discussed above. Furthermore the measurement uncertainty depends strongly on the measurement task and the measurand.

In the computed tomography the measurement is influenced by the X-ray source, the specimen, the detector, the scanning geometry, the environment, the user, the software and even the data evaluation. Therefore there are many components influencing the measurement quantity. In addition indirect data evaluation is done by various algorithms. Many users do not regard the reconstructed voxel volume as the result of a measurement, but rather identify the nominal/actual value comparison, wall thickness analysis and fit of geometric primitives as measurand. Therefore it is necessary that the evaluation of the measurement uncertainty has to consider the uncertainty of subsequent evaluation processes like artefact corrections, surface extraction, registration and nominal/actual value comparison.

3. Simulation-based investigation

A simulation-based investigation of the input quantities on dimensional measurements offers certain advantages: All interference effects covered by the simulation can be activated separately, which allows selective comparisons. Furthermore there are no limitations imposed by availabilities of test objects and CT-systems. Finally the simulation method offers an exact reproducibility of conditions and results and thus the realization of test rows. The drawback is the authenticity grade of the simulation results which has to be verified by comparison with measurements to be sufficient for the intended investigations. The 3D volumes for the investigations were created by a simulation of the CT scan process with 2D X-ray image output followed by a reconstruction algorithm run.

The simulation used a ray-based implementation for the modelling of the X-ray attenuation from the source to the detector. The object under investigation was defined by a composition of primitive geometric objects so that the X-ray intersection length could be calculated analytically. The simulated spectrum of the X-ray source was attenuated according to the intersection length and the energy and material dependent X-ray attenuation coefficients of the object [10]. The detector pixel intensity was derived from the attenuated photon spectrum at the detector pixel position. Quantum noise intensity on the detector was modelled with a Gaussian process and added in relation to the photon numbers and energy distributions at each detector pixel, if required [12]. Scatter effects (LBSA, see above) could also have been generated by the simulations, but were not used in the scope of the presented work.

Verification of the simulation results

The authenticity of the simulation results was verified by the comparison of a simulated 2D X-ray image with a measured X-ray image.The measurement was done with the Fraunhofer EZRT µ-CT system. An alloy test object was x-rayed at 200 kV source voltage with 0.5 mm copper filtering, 180 µA source current and 400 ms exposure time. Afterwards an image correction was performed to reduce detector plane inhomogeneities.

An X-ray simulation was performed with the same test object, scan parameters and scan geometry. The simulation also accounted for quantum noise, scatter radiation and spatial detector impulse response [2][9][12]. The unknown (generally energy dependent) detector efficiency factor was chosen as constant such that the pixel values outside the object area agreed well with the corresponding pixel values in the measured image.

Fig. 1 shows the comparison of the simulated and the measured X-ray projection image. The pixel value profiles along the marked line show an error less than 1% between the local means. A comparison of the standard deviations due to quantum noise between measured and simulated images also showed a good agreement.

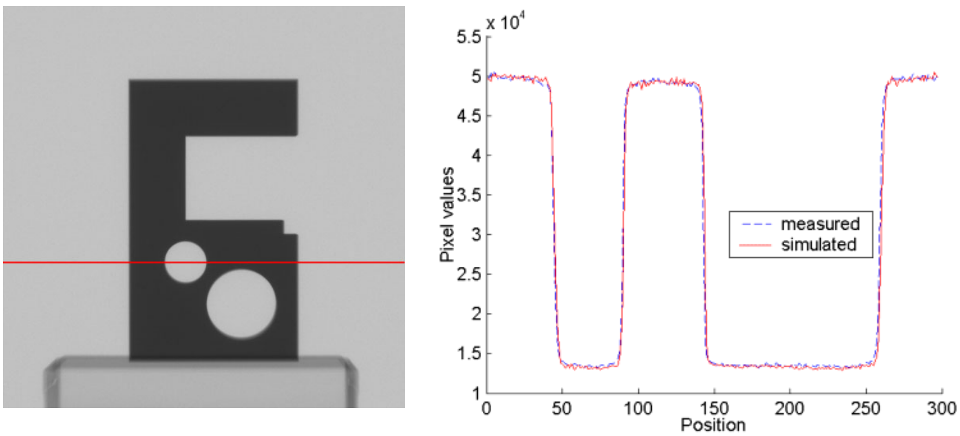

Fig. 1 Comparison of measured and simulated X-ray projection pixel values.

4. Performing the investigations

As outlined above, the X-ray images of a cone ray CT scan geometry with object rotation were created by simulation. The test object was the same alloy test object as in Fig. 1. The detector had a resolution of 512x512 pixels with 400x400 µm pixel size and a pixel value word length of 16 bits integer. The geometric magnification factor due to the scan geometry was 1.43. The number of angular steps was chosen as 400. The applied reconstruction algorithm was a modified version of the Feldkamp algorithm [7].

Afterwards a set of norm geometries was fitted to the iso-grayvalue surface that was extracted from the reconstructed 3D volume by a process described in [11]. There were ten norm geometries fitted to the test object (8 planes and two cylinders with 4000 fit points each). From the geometry fit two results can be obtained directly: The measurement error from the comparison with reference values and a quality value for the measurements from the standard deviation of the fitpoints.

In the following, the dependency of the measurement error and the measurement quality on various influence quantities was investigated systematically: For the dependency on the X-ray source the source spectrum pre-filtration was varied. For the dependency on the adjustment accuracy of the mechanical positioning system various alignment inaccuracies were simulated. For the dependency on the quantum noise the detector exposure time was varied.

Source pre-filtration

The usage of a polychromatic X-ray source for CT instead of a monochromatic one leads to the well known effect of beam hardening in the reconstructed volume [1][8]. The pre-filtration of the source spectrum is a common method to oppose this effect.

In order to investigate the effect of beam hardening on dimensional measurements, tomographies of the alloy test object at a constant source voltage of 200 kV and variable copper (Cu) pre-filtration with filter thicknesses from 0 mm to 4 mm were simulated. For conformance with the technical data of the Viscom X-ray tube at Fraunhofer EZRT an inherent filtration of the 0.8 mm beryllium window was also added to all cases. Quantum noise and scatter effects, as well as spatial detector impulse response simulation were turned off for this case.A tomography with a monochromatic X-ray source at 150 keV and otherwise the same settings was created for reference.

Alignment accuracy

In the ideal case the actual scan geometry has to be known exactly as input for the reconstruction algorithm. Misalignments of the object rotation axis and the detector cause artefacts in the reconstructed volume. Several misalignment scenarios were investigated in order to identify the necessary alignment accuracy.

In the first scenario, the detector was tilted by 1° rotations around its center, namely around the x-axis, a y-parallel axis and a z-parallel axis (see Fig. 2 left). Secondly, the object rotation axis was tilted out of its z-parallel position by a rotation of 1° around the y-axis. In the last scenario the object rotation axis was shifted towards y-direction by 350 µm and 700 µm, respectively (see Fig. 2 right). These shifts correspond to an approximate shift of the object projection on the detector by one and two pixels, respectively. All tomographies were carried out under monochromatic conditions without quantum noise, scatter effects and spatial detector impulse response simulation, so that an isolated investigation of the geometry effects on dimensional measurements was guaranteed. A

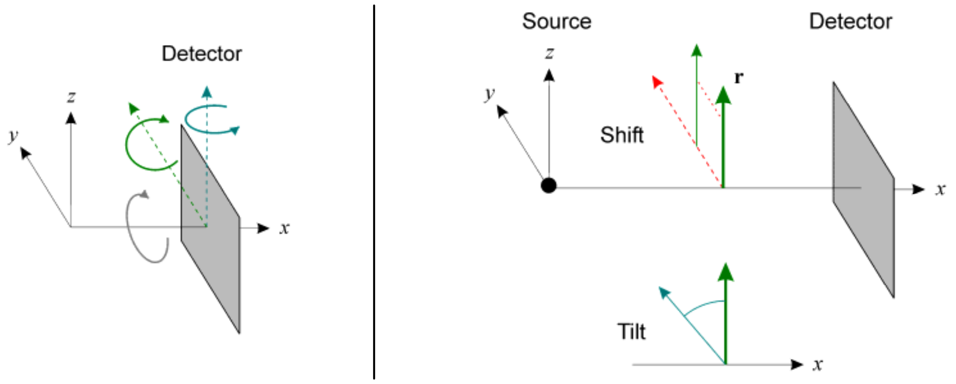

Fig. 2 Misalignments of the detector (left) and of the object rotation axis (right).

tomography with ideal geometric alignment and otherwise the same settings served as a reference case.

Detector exposure time

The reason for quantum noise lies in the statistical nature of X-ray attenuation. The detector spectral signal to noise ratio due to quantum noise is approximately equal to the mean number of incident photons [9][12]. The number of incident photons is both proportional to the detector exposure time and the source current.

For the investigation of the dependency of quantum noise on dimensional measurements, three tomographies were performed, each with a polychromatic X-ray source operating at 200 kV source voltage, 100 µA source current and 0.5 mm copper pre-filtration. The detector exposure time was set to 100 ms, 200 ms and 400 ms, respectively. Quantum noise simulation was activated for this case, but scatter effects and spatial detector impulse response effects were omitted. An additional tomography with the same settings but no quantum noise simulation was created for reference.

5. Results

For each scenario seven dimensions from the test object were measured, two of which were inner radial dimensions, one was an inner linear measure and four were outer linear measures (see Fig. 3). The standard deviation of the norm geometries' fit points was also

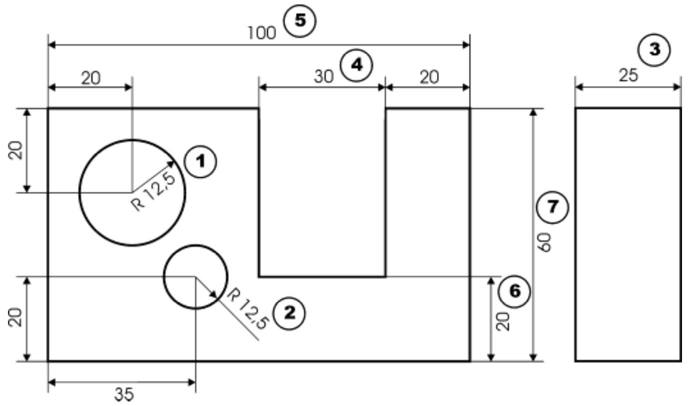

Fig. 3 Measures of the alloy test object. The seven measurements performed with the fitted geometries are marked with encircled numbers.

recorded as a quality value for the measurements. In the graphs in the following sections the mean of the 4-sigma values (four times the standard deviation) over all of the ten geometry fits are shown. The average measurement errors over all of the seven measurements within one scenario are shown in the graphs as diamonds and their ranges are depicted with lines.

Source pre-filtration

Fig 4 shows the 4-sigma values and the measurement errors at different pre-filtration levels. Fig. 5 (right) shows the voxel value profiles along the line marked in Fig. 5 (left). Both the 4-sigma values and the measurement errors are highly affected by the so called *cupping effect* introduced by the beam hardening [1][8]. The cupping effect can be seen on the profiles in Fig. 5 especially at low pre-filtration and diminishes with increasing filter thickness. For the present test object's tomography 4 mm copper thickness seems to be

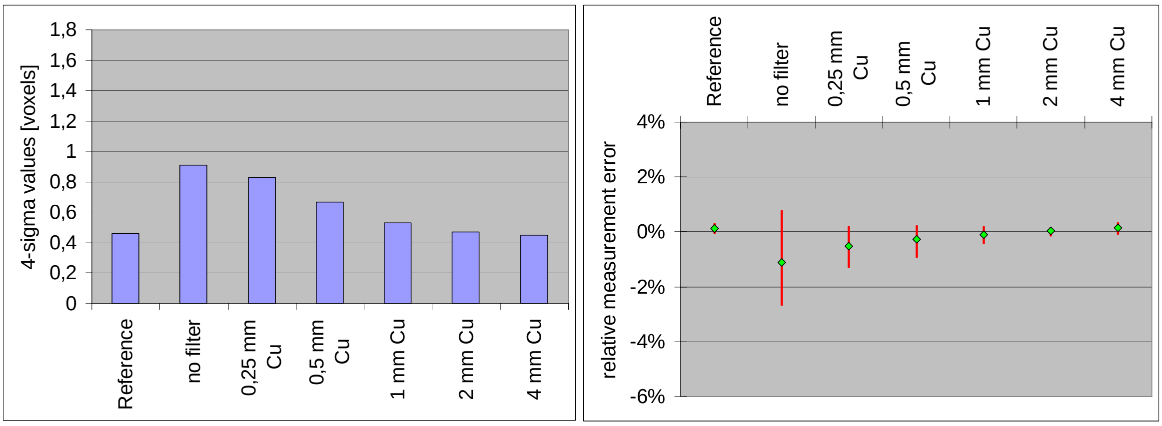

Fig. 4 Measurement quality according to the 4-sigma values (left) and relative measurement errors (right) for different source prefiltration, along with the monochromatic reference case.

enough to eliminate the cupping and to establish conditions close to the reference case with a monochromatic X-ray source. Note that for adequate dynamic levels in the projection images the strong attenuation of the X-ray radiation at 4 mm copper filtration has to be compensated either by a relatively high source current or a higher exposure time. The latter lengthens the duration time of the tomography while the former might be limited due to the X-ray tube specifications.

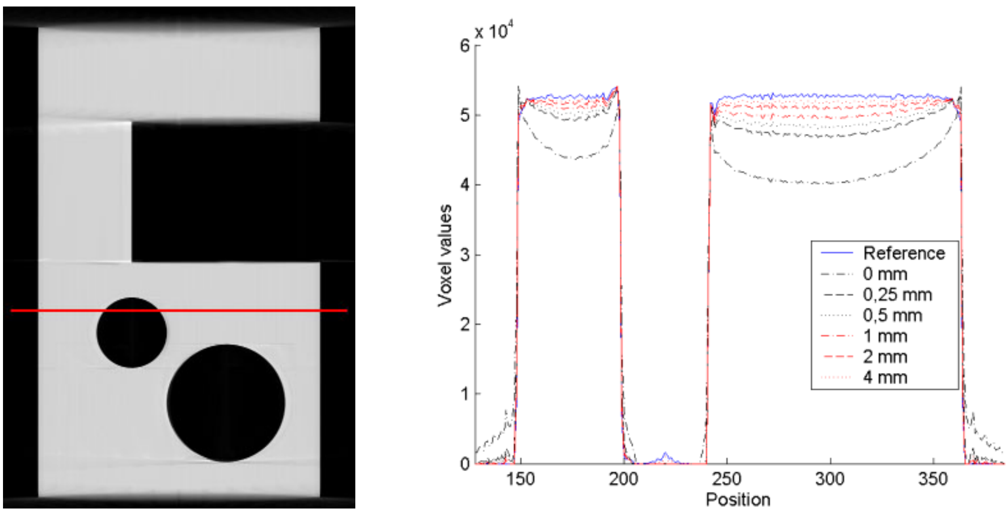

Fig. 5 Voxel value profiles in the reconstructed volume (right) along the marked line (left) for different source prefiltrations.

Alignment accuracy

Fig. 6 shows that the detector tilt of 1° around the x-axis has the most severe effect both on the 4-sigma values and on the measurement errors. The second strongest effect is due to the rotation axis shift towards y-direction by 700 µm.

Another noticeable influence on the measurement results has a rotation axis tilt of 1° around the y-parallel axis. At this scenario also a total tilt of the reconstructed object by 1° in the voxel volume versus the reference case can be observed, which was verified by a comparison of the main axes of inertia.

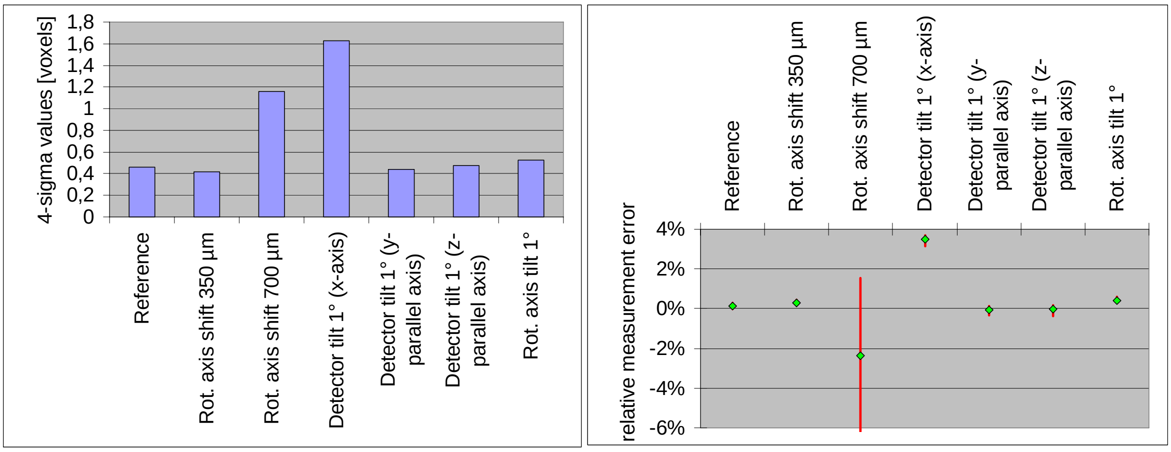

Fig. 6 Measurement quality according to the 4-sigma values (left) and relative measurement errors (right) for different geometry misalignments, along with the reference case with accurate alignment.

The tilts of the detector around the y-axis and around the z-parallel axis lead to hardly any changes, as did the rotation axis shift towards y-direction by 350 µm. Thus an alignment accuracy of about a corresponding half pixel shift of the object projection on the detector seems to be sufficient. In order to investigate the maximum tolerable detector rotation around the x-axis, a further investigation was carried out, as described in the next section.

Investigation of the maximum tolerable detector rotation around the x-axis

For this investigation a thin cylinder with a sphere at each end was used as test object, as depicted in Fig. 7 (left). A tomography with this object was performed under the same scan geometry as the alloy test object and with a monochromatic X-ray source. The object was positioned for its projections to occur in the upper left area of the detector images. Now the detector was rotated by 1, 1/2, 1/4, 1/8, 1/16 and by 0 pixels for reference. Here the pixel value corresponds to the outer vertical distance of the upper detector edge to the aligned case. A rotation by 1° with the currently used 512x512 pixel detector would correspond to a distance of approx. 4.5 pixels.

Now the absolute by-voxel differences between the reference volume and the volumes with object tilt were computed. In Fig. 7 (right) the voxel-maximum of these difference volumes is shown. From this result one can expect that a tilt of less than 1/4 pixels won't have any influence on geometry fits and thus on dimensional measurements, because the error will be in the order of magnitude of reconstruction artefacts and noise.

Detector exposure time (quantum noise)

Fig. 8 shows, that at 100 ms exposure time the quantum noise has a distinct influence on the 4-sigma values and the measurement errors. This influence diminishes with longer

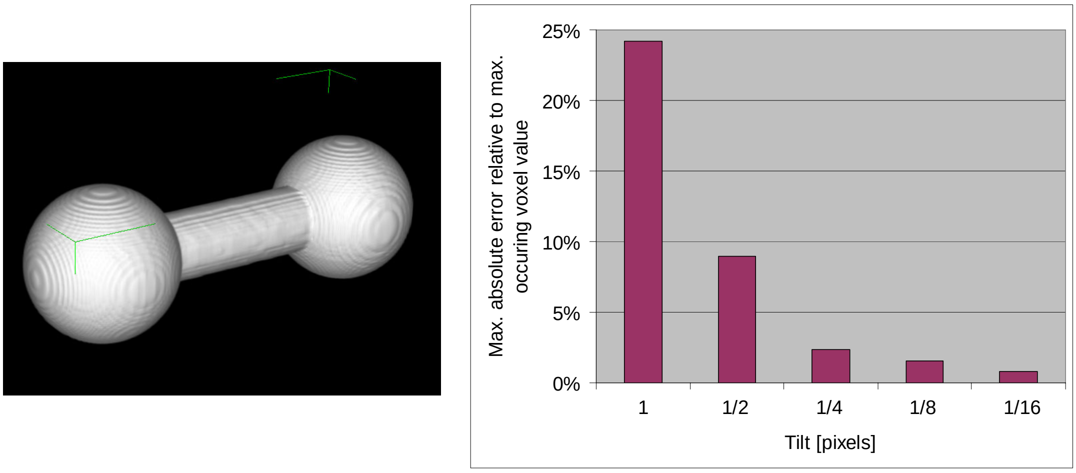

Fig. 7 Object for investigation of the maximum tolerable detector rotation around the x-axis (left). The maximum of the absolute error relative to the maximum of the occurring voxel values is shown on the right for different detector tilts.

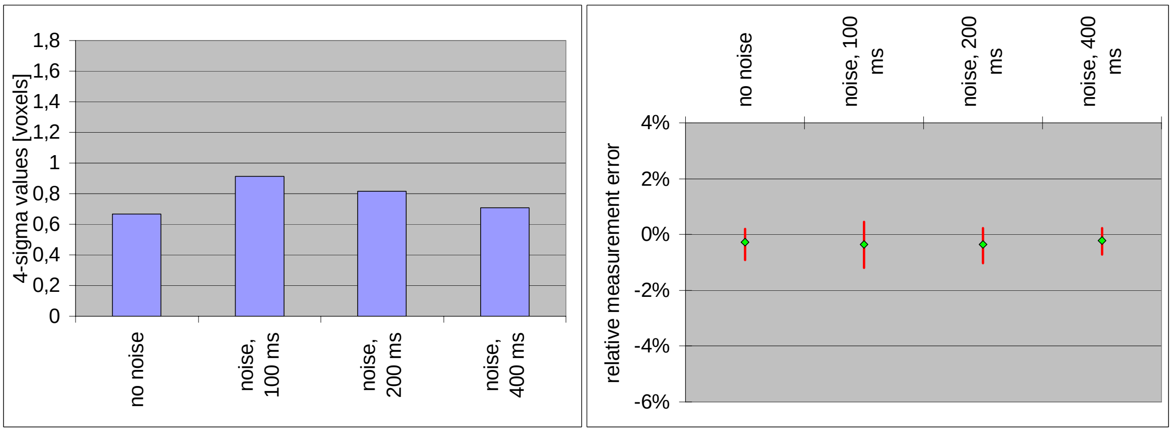

Fig. 8 Measurement quality according to the 4-sigma values (left) and relative measurement errors (right) for different detector exposure times, along with the reference case without quantum noise.

exposure time. The conditions at 400 ms are almost the same as in the noise free reference case. The signal-to-noise ratios for the first projection image, respectively, are presented in Table 1. for comparison.

T_{exp}	Background area	Object area
100 ms	36.6 dB	30.7 dB
200 ms	39.6 dB	33.4 dB
400 ms	42.6 dB	36.3 dB

Table 1 Signal to noise ratios due to quantum noise in the first projection images, respectively, for the tomographies with different detector exposure times.

6. Conclusions

In the presented work the dependency of the measurement error and the measurement quality on various influence quantities was investigated systematically with the help of a simulation of the X-ray process. The output of the simulation was found to agree well with authentic X-ray projection images.

From each of the three major parts of the X-ray system, i.e. the X-ray source spectrum, the mechanical positioning system and the X-ray detector, one parameter was varied exemplarily. The source pre-filtration was figured out to have a distinct influence on the measurement quality, since it could help to lower the cupping effect to a negligible level by a copper thickness of 4 mm for the current object. The most critical alignment parameters regarding the mechanical positioning system were discovered to be the detector tilt around the x-axis and the rotation axis shift towards y-direction. Detector quantum noise could be handled with long enough exposure time, which was 400 ms for the given scan parameters.

With the help of this method the most severe influence quantities on the CT measurement process can be identified. Only a small selection of all possible influence quantities was evaluated here. Further work would be to derive analytic relationships between scan parameters and the measurement uncertainty in order to set up a model equation for the GUM analysis.

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