Influence of detector misalignments on different geometrical and dimensional measurands using a dedicated test specimen

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Abstract
An important focus of research in Industrial X-ray Computed Tomography (CT) is to determine the task-specific measurement uncertainty of CT measurements numerically by using simulations. For this, all relevant influence factors need to be identified and quantified. It is known, for example, that geometrical misalignments of the detector lead to measurement deviations if the reconstruction does not consider these misalignments. This contribution uses computer simulation of CT data to investigate the influence of geometrical misalignments of the detector on several measurands found in typical measurements tasks in the industry. A newly developed test specimen with a broad variety of features is used for this study. Angular and positional detector deviations are systematically introduced into the simulations and deliberately left uncompensated during the CT reconstruction. The resulting measurement deviations are shown and discussed.

Keywords: task specific numerical measurement uncertainty, dimensional metrology, geometrical misalignment

1 Introduction

This study is part of a series of investigations carried out for the research project "CTSimU – Radiographic Computed Tomography Simulation for Measurement Uncertainty Evaluation". The aim of this project was to create a list of requirements for CT simulation software and derive a framework of tests to qualify CT simulation software with regard to the correct simulation of physical laws and characteristic effects and functionalities. In order to develop in a second funding period methods and procedures to successfully build digital twins of CT systems and a test framework for verifying how well a digital twin performs. The results of these first two projects should then enable the determination of the task-specific measurement uncertainty by simulation (planned third project).

For these purposes, it is important to know how different measurands are affected by different influencing factors. In a former publication the authors already investigated the influence of projection noise on different measurands [1]. A further question is how uncertainties in the CT geometry affect the results of dimensional measurands. In this contribution the geometrical misplacements and misalignments of the detector were investigated. If the geometrical parameters of the detector do not match with the parameters provided to the reconstruction algorithm, measurement deviations are expected. A few studies already discussed the influence of detector angular misalignments on dimensional measurements [2-7]. They showed that angular detector misalignments lead to a varying severity of measurement deviations.

Ferucci et al. [2] presented a review of research efforts for the development of geometrical calibration procedures for CT systems. They showed methods and results regarding how different geometrical misalignments affect the measurement results. Ametova et al. [3] introduced a geometrical error model to determine the measurement uncertainty as an alternative method to the Monte-Carlo simulation. Aloisi et al. [4] examined how misalignments of the detector in horizontal direction affect dimensional measurements, especially sphere centre-to-centre distances, diameter and form measurements. For this purpose, they used a tactile coordinate measurement machine (CMM) calibrated ball bar consisting of seven equally spaced spheres with a nominal sphere diameter of 1.59 mm and sphere centre-to-centre distances ranging from 5 mm to 30 mm. For their investigation they physically misaligned the detector of the CT-System around the horizontal axis of the detector to study the influence of the detector out of plane rotation. They compared their results to the correctly aligned setup. The misalignment had an influence on features scanned in vertical direction. The measured errors increased consistently with increasing rotation. Form measurements did not show a clear trend between the aligned and misaligned configuration. Muralikrishnan et al. [5] conducted a sensitivity analysis of detector geometry errors. They performed simulations with defined misaligned detector positions and compared two simulation approaches, a radiograph-based method and a single-point ray tracing method. Their test specimen consists of 125 spheres and is used to analyse the sphere centre-to-centre distance errors and sphere form errors. Based on their results, they gave recommendations how the spheres should be positioned in order to detect geometry errors. Sbettega et al. [6] continued the study of Aloisi et al. [4] and performed a simulation study of different detector angular rotations in all directions of the coordinate system (0.5°, 1°, 1.5°) by using a ball bar plate with 56 ruby spheres. They examined centre-to-centre distances in horizontal, vertical and diagonal direction. Kumar et al. [7] showed in their simulation study how different geometrical errors affect dimensional measurements. They analysed three research questions: (1) how the object position and orientation affect the scan

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volume, (2) the effect of geometrical misalignments under different object configurations and (3) how different sizes of the objects influence the extent of measurement errors. For this study they used a test specimen with two spheres which are connected through a rod. The results showed that the object position and orientation had an influence on the measurement results if an error in geometrical parameters had an influence. A detector tilt, as well as a misalignment of the source lead to similar measurements errors at all investigated configurations. They concluded that a detector tilt should amount to less than 1° for an accurate measurement. However, these studies were carried out based only on a limited sample of geometrical features, e.g. spheres and thus measurand types, i.e. form errors, centre-to-centre distance measurements and diameters.

This contribution focuses on the influence of the detector misalignments on the measurement results for serval types of measurands. The investigation is based on a novel test specimen developed in the CTSimU project: the *multi-geometry cuboid*. This test specimen provides many geometrical features of different size and shape and thus different measurands, such as form errors, location and orientations errors, diameters, distances including point-to-point distances, and torus radii. [8] Besides that, the applicability of the novel *multi-geometry cuboid* to detect and quantify geometrical errors of CT simulators is also tested in this contribution.

2 Materials and Methods

The geometry of the simulation scenario for the investigation of different detector misplacements and misalignments was designed close to a realistic CT system. In order to isolate the effect of the geometrical misalignment of the detector, the simulations were carried out without any other quality-decreasing effects, e.g., noise or detector unsharpness. In Figure 1 the scenery is illustrated.

The source-object distance (SOD) was set to 127.5 mm and the source-detector distance (SDD) was set to 2125 mm. An ideal energy-integrating flat panel detector was used in the simulations: the thickness of the scintillator was assumed to be zero and the detector was thus assumed to be infinitely thin. The incoming radiation energy on each pixel is linearly converted to grey values without losses. The parameters of the detector are 1000 px × 1000 px with a pixel size of 0.680 mm × 0.680 mm. This leads to a magnification of about 16.66 and thus a voxel size of 40.8 µm. The point source emits a polychromatic X-ray spectrum with a maximum tube acceleration voltage of 150 kV and a 4 mm aluminium filter. The power of the tube, the integration time and the detector response were arranged such that the grey values reach a maximum of 60000 at a free beam.

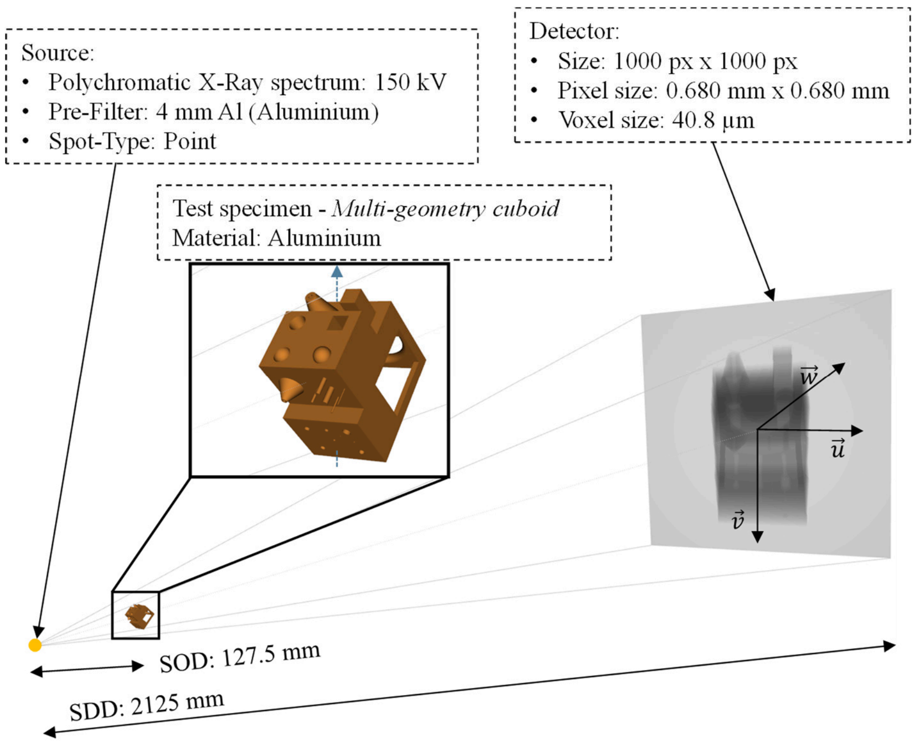


Figure 1: Setup of the simulation with the coordinate systems of the detector and the test specimen – the *multi-geometry cuboid*.

The *multi-geometry cuboid* was selected mainly because of its flexibility regarding measurands. So far most of the test specimens used in literature feature only spheres or calottes as geometries, limiting the investigations on different more complex measurands [2-7]. The *multi-geometry cuboid* has a size of 22.2 mm x 21.8 mm x 15.0 mm and contains in total 37 different internal as well as external geometrical features that allow a high number of different measurands of different complexity based on planes, cylinders, cones, tori and spheres. In total 68 measurands are derived from the internal and external geometrical features aiming to cover as many measurands typically found in industry as possible. The derived measurands can be categorised in form, location and orientation and geometrical measurands, like diameter, torus radii, distances, point-to-point distances. This relatively high number helps to investigate the behaviour of different measurands to different geometrical misalignments of the detector more thoroughly. A detailed description of the *multi-geometry cuboid* is given in [8]. The test specimen material in the simulations was aluminium (density: $\rho \approx 2.7\ \mathrm{g/cm^3}$). In order to reduce cone-beam artefacts and optimize the material penetration lengths, the test specimen was tilted horizontally by 40° towards the source, see Figure 1.

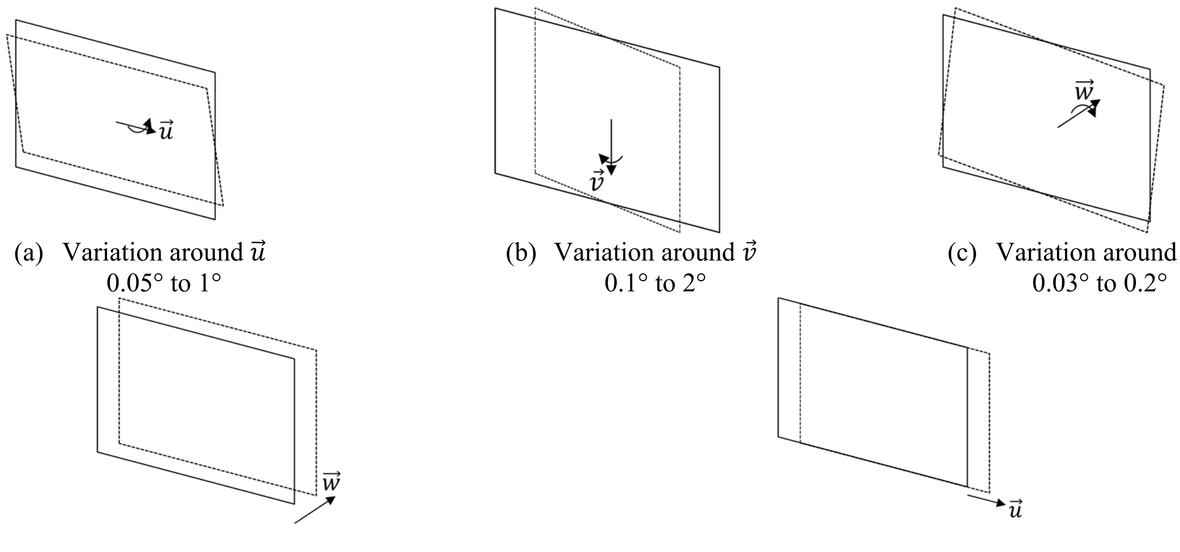
The aim of this contribution is to investigate the behaviour of the different measurands towards detector misplacements and misalignments in comparison to an ideal setup (without any geometrical errors). To achieve this, the detector position was incrementally shifted in small steps along the horizontal and centre axes. In the same manner, the detector was incrementally tilted around its three principal axes, vector $\vec{u}$, vector $\vec{v}$, vector $\vec{w}$. Figure 2 shows schematically the different misalignments and misplacements. Table 1 presents an overview of the different parameter values. The initial values were chosen according to literature research and then adapted incrementally.

Table 1: Overview of the used different angular tilts of the detector around the corresponding axes and the used values for the detector shift along the horizontal and central axes

Variation (tilt) around:		
$\vec{u}$ in °	$\vec{v}$ in °	$\vec{w}$ in °
0.05; 0.10; 0.15; 0.20; 0.30; 0.40; 0.50; 0.60; 0.70; 0.80; 0.90; 1.00	0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9; 1.0; 1.1; 1.2; 1.3; 1.4; 1.5; 1.6; 1.7; 1.8; 1.9; 2.0	0.03; 0.04; 0.05; 0.10; 0.11; 0.12; 0.13; 0.14; 0.15; 0.16; 0.17; 0.18; 0.19; 0.20

Shift of detector along:	
$\vec{u}$ in µm	$\vec{w}$ in µm
0.05; 0.10; 0.20; 100; 200; 300; 400; 500	0.05; 0.10; 0.20; 100; 200; 300; 400; 500
Correspond to 0.00007; 0.00015; 0.0003; 0.1471; 0.2941; 0.4412; 0.5882; 0.7353 of the pixel size	Correspond to 100.000002 %; 100.000005 %; 100.000009 %; 100.005 %; 100.009 %; 100.014 %; 100.019 %; 100.024 % of the initial magnification

Compared to [3, 5] a finer sampling of the variation step sizes was chosen to better sample the region of the onset of significant measurement deviations. A measurement deviation is seen as significant if it is higher than 10 % of the voxel size. This threshold was selected heuristically and inspired by [9].



(a) Variation around $\vec{u}$ 0.05° to 1°

(b) Variation around $\vec{v}$ 0.1° to 2°

(c) Variation around $\vec{w}$ 0.03° to 0.2°

(d) Shift of detector along $\vec{w}$ 0.05 µm to 500 µm

(e) Shift of dectector along $\vec{u}$ 0.05 µm to 500 µm

Figure 2: Schematic illustration of the different angular misalignments (a) to (c) and shift of the detector (d) and (e).

Another research focus was the combination of the different angular misalignments of the detector. The aim was to investigate how multiple detector tilts affect the results of different measurands. The parameter values were selected according to the results of the isolated detector misalignments. The initial values were chosen based on the results of the investigation of the isolated geometrical errors (the parameter of the first measurands presenting a significant measurement deviation). An overview of the simulated combinations is depicted in Table 2.

Table 2: Combined variation of the angular tilts of the detector

Variation around:								
$\vec{u}, \vec{v}$ in °		$\vec{u}, \vec{w}$ in °		$\vec{v}, \vec{w}$ in °		$\vec{u}, \vec{v}, \vec{w}$ in °		
0.2	1.4	0.2	0.14	1.4	0.14	0.2	1.4	0.14
0.3	1.5	0.3	0.15	1.5	0.15	0.3	1.5	0.15
0.4	1.6	0.4	0.16	1.6	0.16	0.4	1.6	0.16
0.5	1.7	0.5	0.17	1.7	0.17	0.5	1.7	0.17
0.6	1.8	0.6	0.18	1.8	0.18	0.6	1.8	0.18
0.7	1.9	0.7	0.19	1.9	0.19	0.7	1.9	0.19
0.8	2.0	0.8	0.20	2.0	0.20	0.8	2.0	0.20

The software aRTist 2.10 (BAM, Berlin) was used for conducting this study. The flat field correction of the projections was done with the *CTSimU* software toolbox [10-11]. The CT reconstruction, the surface determination and the dimensional evaluation were executed with VGStudio Max 3.4 (Volume Graphics, Heidelberg). In all cases, the misalignments and misplacements were not compensated during the reconstruction. The standard Feldkamp-Davis-Kress (FDK) - algorithm was used for reconstruction. The surface in the reconstructed volumes was determined using the local adaptive method [1]. Afterwards the volumes were registered and aligned to the given coordinate system. The developed measurement plan was then conducted on the determined surface [8]. This process was carried out in an automated manner to minimize the user's influence on the measurements. In order to detect the impact of the geometrical errors on the 68 measurands, the results of the simulation scenarios under parameter variations were compared to the ideal simulation (i.e., the given scenario with no detector misplacement and misalignment).

3 Results

The results of the described investigations are presented in this section. First, the result of the different angular detector tilts will be discussed, before the effect of the detector misplacements will be described. After that, the result of the combined detector tilts will be given. Figure 3 illustrates the results of the different angular detector tilts around all three axes: (a) variation around $\vec{u}$, (b) variation around $\vec{v}$, (c) variation around $\vec{w}$.

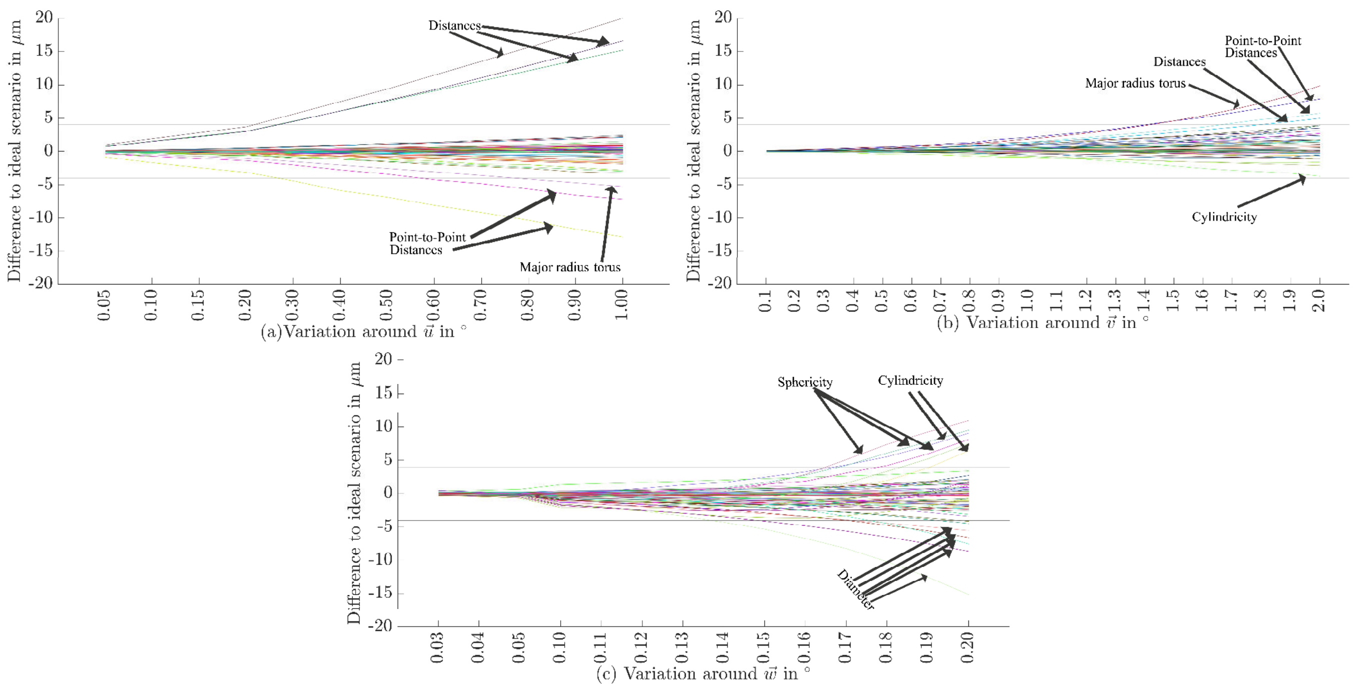


Figure 3: Results of the simulations with stepwise variation of the detector angular tilt. The difference to an ideal setup (i.e. with no misalignment) is shown for the three types of variations investigated: tilts around all three axes (a, b, c). The grey lines indicate ± 4 µm, which is 10 % of the voxel size.

The results indicate that different measurands are sensitive to different misalignments. Angular tilts of the detector around its horizontal axis ($\vec{u}$) and around its normal ($\vec{w}$) quickly lead to significant measurement deviations from the ideal case (i.e., > than 10 % of the voxel size) for small variations starting with 0.14° and 0.2° for variations around $\vec{w}$ and $\vec{u}$, respectively. Measurands like distances between the centre of two calottes in the horizontal direction, point-to-point distances in horizontal direction, between an internal feature and an external feature and major torus radius show significant deviations if the detector is tilted around the horizontal axis ($\vec{u}$). Geometrical measurands like diameter, sphericity and cylindricity show an increase in the deviation if the detector tilt is around the central axes, the $\vec{w}$. The diameter is the first measurand that shows a significant measurement deviation. If the detector has an angular tilt around the vertical $\vec{v}$, measurands like major radius of a torus or the form error, cylindricity, deviate most from the ideal scenario. However, only the major radius of the torus and point-to-point distances and distances show a significant measurement deviation if the detector is tilted around the vertical $\vec{v}$ in these parameter variations.

Positional offsets of the detector lead to variations in the magnification (shift along $\vec{w}$) and of the projected centre of rotation (shift along $\vec{u}$). The results of these detector misplacements (Figure 4) show a significant influence (measurement deviation ≥ 10 % of the voxel size) on the dimensional measurements for detector shifts that exceed half a pixel size (>340 µm). Measurands like distances seem to be sensitive to variations of the magnification (Figure 4-(d)). The sphericity shows a small increase, but no significant deviation.

On the other hand, measurands like the cylindricity, the point-to-point distances and cylindricity indicate a shift along the projected centre of rotation $\vec{u}$ (Figure 4-(e)). Only the smallest cylinder and the point-to-point distances show a significant deviation between these parameter variations.

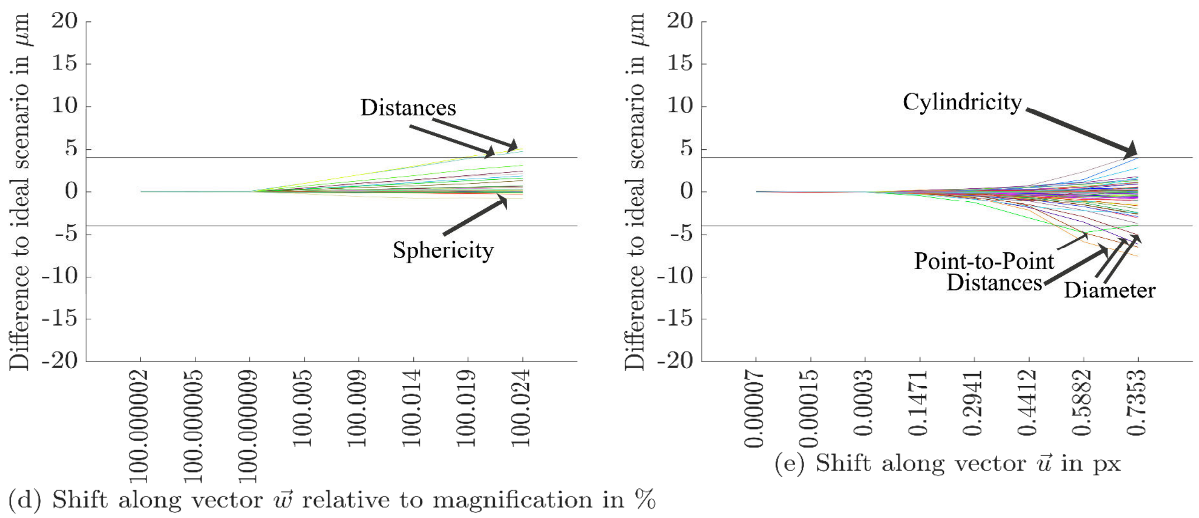


Figure 4: Results of the simulation with stepwise variation of the detector position. The difference to an ideal setup (i.e., with no misalignment) is shown for the two types of variations investigated: magnification (d) and projected centre of rotation (e). (d) is illustrated in relation to the magnification of 16.66. The detector was shifted until 100.24 % of the initial position. (e) is illustrated in relation to the pixel size. The detector was shifted until about 0.74 pixel. The grey lines indicate ± 4 µm, which is 10 % of the voxel size.

For all rotational and positional variations, one can recognize a steady (in first approximation linear) increase of the difference to the ideal scenario with the increase of the parameter variation. Only location errors seem to be stable to different detector misplacements and misalignments.

A further objective of this study is to investigate how different combined angular tilts of the detector affect the different measurands. The results of the simulated combinations, listed in Table 2, are presented in Figure 5.

In Figure 5-(a) the effect of the variation around the horizontal axis ($\vec{u}$) in combination with the variation around the vertical axis ($\vec{v}$) is shown. The distances and the point-to-point distances show the most increase in the deviation. However, only the distances and major torus radii exhibit a significant measurement deviation in the first combination. The point-to-point distances between an internal and external feature only show a significant measurement deviation from a combination from 0.5° tilt around $\vec{u}$ and 1.7° tilt around $\vec{v}$. These measurands also showed the steepest increase with only a variation around the horizontal $\vec{u}$ (see Figure 3-(a)).

A variation around the horizontal axis ($\vec{u}$) and its normal ($\vec{w}$) leads already to a significant deviation from the ideal setup for measurands like diameters caused by a tilt around $\vec{u}$ of 0.2° and around $\vec{w}$ of 0.14°. Distances exhibit a significant deviation at the next combination (rotation around $\vec{u}$ = 0.3° and $\vec{w}$ = 0.15°) (see Figure 5-(b)). Further measurands that show significant deviations are sphericity, cylindricity and major torus radii. The effect of the detector tilt combination around the $\vec{v}$ and $\vec{w}$ is shown in Figure 5-(c). The combination of 1.4° around $\vec{v}$ and 0.14° around $\vec{w}$ shows, like the isolated detector tilts, already a significant measurement deviation in the measurands sphericity, cylindricity, point-to-point distances and diameters. The sphericities have the steepest increase. In comparison to the variation shown in Figure 5-(a) more measurands show a steep increase.

The result of the variation around all three axes is presented in Figure 5-(d). As well as in Figure 3 and Figure 5-(a) the measurands distances, sphericity, cylindricity, diameter, major torus radii and point-to-point distances represent the steepest increase. The combination of 0.2° around $\vec{u}$, 1.4° around $\vec{v}$ and 0.14° around $\vec{w}$ already leads to significant deviation from the ideal setup for the distances. Point-to-point distances show the first significant deviations with the third combination (0.4° around $\vec{u}$, 1.6° around $\vec{v}$ and 0.16° around $\vec{w}$).

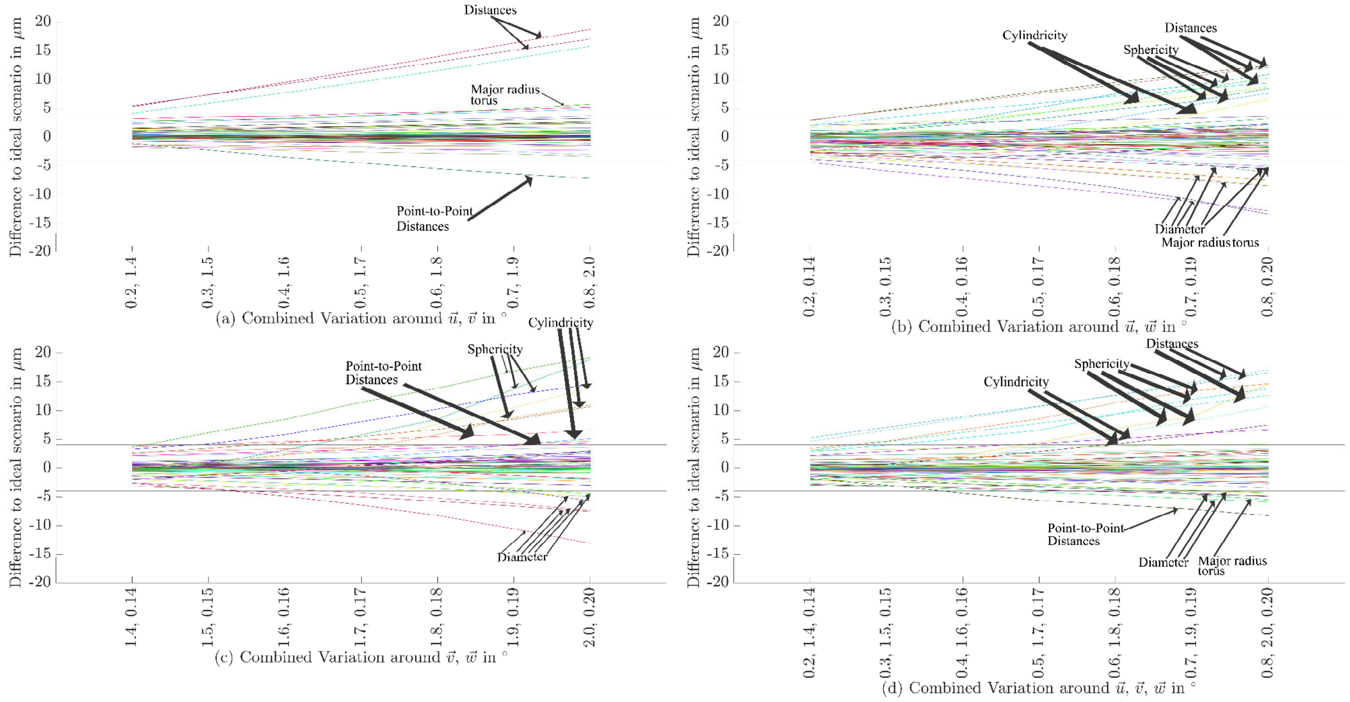


Figure 5: Results of the simulation with stepwise variation of the angular tilts of the detector position. The difference to an ideal setup (i.e., with no misalignment) is shown for the four types of variations investigated: combined tilts of the $\vec{u}$ and $\vec{v}$ (a), combined tilts of the $\vec{u}$ and $\vec{w}$ (b), combined tilts of the $\vec{v}$ and $\vec{w}$ (c), combined tilts of the $\vec{u}$, $\vec{v}$, $\vec{w}$ (d). The grey lines indicate ± 4 µm, which is 10 % of the voxel size.

4 Summary and Outlook

This contribution has provided an overview about the effect of detector misplacements and misalignments on a novel dedicated test specimen – the *multi-geometry cuboid*. This test specimen contains various geometrical features of different size and forms (e.g., planes, cylinders, cones, tori and spheres) and thus several derived dimensional measurands (68 different measurands). For the investigations a generalized CT system with a realistic geometry and X-ray spectrum was arranged in the simulation software aRTist 2.10 (BAM). The simulations were conducted with stepwise parameter variations of the detector misalignment (angular tilt around all three axes) and misplacement (shift along magnification and horizontal axes). Two objectives were investigated: 1) an isolated consideration of the different detector misplacements and misalignments; 2) an analysis of the multiple angular detector tilts and their influence on different dimensional measurands.

The results of the isolated simulation of the misplacements and misalignments demonstrated that measurands like form errors react most sensitively towards angular tilts around the planar normal of the detector ($\vec{w}$) and around its horizontal axis perpendicular to the axis of CT rotation ($\vec{u}$). Tilts around the projected axis of CT rotation ($\vec{v}$) indicate a steady but slight increase of the measurement deviation as well. Torus radii, diameters and form errors like sphericity and cylindricity are the most sensitive to those misalignments around the vertical axis. Multiple detector misalignments were analysed as well. Diameters, distances, point-to-point distances and sphericity react most sensitively to multiple detector misalignments. Those measurands which are sensitive to single detectors misalignments show the same behaviour when applying multiple detector misalignments. These results indicate that the design of the *multi-geometry cuboid* is suitable to detect and quantify different geometrical detector misalignments and misplacements.

It can be concluded that it is important to know the exact geometry parameters of the detector for successfully building a digital twin of a real CT system and the subsequent determination of the task specific measurement uncertainty. Further investigations should focus on misplacements and misalignments of the source and the stage, even though they are partly included in this study implicitly, apart from the importance to analyse more effects like detector unsharpness, beam hardening or scattering in an idealised simulation to estimate their contribution to the measurement uncertainty. The long-term goal of this series of investigations is to estimate the task specific measurement uncertainty numerically by using a Monte-Carlo method. To reach this goal it is mandatory to determine all relevant effects and their corresponding distributions. Besides the study of isolated effects, investigations into interactions of the different effects and their influence on different measurands should also be conducted.

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