Simulation-based correction of systematic errors for CT measurements

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Abstract
A large number of influencing quantities can induce measurement deviations for dimensional measurements using computed tomography. The article describes a newly developed simulation-based correction method for computed tomography coordinate measurements. Using a steel gauge block it is demonstrated that the method can significantly reduce the deviation of the measured surface from the real form of the measurement object. The computed tomography system used has a maximum acceleration voltage of 130 kV. Therefore, a steel gauge block is a relatively challenging measurement object due to the likely occurrence of beam hardening artefacts. The results show that, for a given computed tomography system, the described method can extend the range of objects for which dimensional measurements are feasible.

Keywords: X-ray computed tomography, simulation, artefacts, correction, systematic error, ray tracing

1 Introduction

During the last decade, X-ray computed tomography (CT) has developed into an established and accepted measurement technique for dimensional metrology [1]. An important reason for this development is the possibility to measure complex parts including inner structures in one measurement, which is not possible with tactile or optical methods.
A dimensional CT measurement consists of multiple steps. First, two-dimensional radiographic projections from a large number of angles are taken. These projections are then reconstructed to a grey value voxel model, which represents the distribution of the X-ray absorption coefficients in the measured volume. For a dimensional measurement, a surface needs to be extracted by segmentation from the volume data.
Dimensional CT measurements therefore consist of comparably many and complex process steps which all cause CT specific influence factors. Examples are beam hardening and scattered radiation, which are unique to CT measurements [2]. For parts made of materials with relatively low density and atomic numbers like plastics, these influences usually have a negligible influence on the measurement result. For strongly radiopaque materials like steel, these effects can often already be identified visually in the projection data and cause artefacts in the volume data leading to erroneous surface determination and thus an increased measurement uncertainty [3]. This motivated the development of multiple methods to identify these artefacts in the volume data or minimise their influence on the measurement result [4, 5].
A possible tool for these correction algorithms is the simulation of CT measurements. The field of CT measurement simulation is currently researched to, e.g., realistically determine measurement uncertainty numerically. As all error sources are modelled as realistically as possible, these simulations can also be used for systematic correction of measurement errors.
This contribution presents a method to use those simulation results to correct systematic measurement deviations of real CT measurements. The method is demonstrated using a gauge block and the metrological relevance discussed.

2 Simulation based correction of coordinate measurements

The method which is presented in the following reduces measurement deviations by correcting the extracted surface data from a CT measurement. For the determination of the surface coordinates, the influence of artefacts present in the volume data should already be minimised. E.g. global ISO50 surface determination produces significant systematic measurement deviations in volumes with artefacts. Therefore, state of the art locally adaptive surface determination is preferable as it is more robust against artefacts [3]. However, even for these, systematic measurement deviations cannot be avoided completely. Therefore, methods for correcting surfaces based on tactile or optical reference measurements with smaller measurement uncertainties have been developed [6]. These reference measurements only need to be performed for one part from a series to determine the local systematic deviations and subsequently correct the measurements of all other parts. This scheme will also be adapted in the following, only that the reference measurements are obtained by simulations based on a CAD modell with the expected part geometry.
There are various simulation tools commercially available (e.g., aRTist [7], Scorpius XLab [8] and CIVA CT [9]) as well as tools developed for research (e.g., SimCT of FH Wels [10]). One of the intended applications is the numerical determination of the task specific measurement uncertainty for a given CT measurement. For this purpose, a trustworthy representation of the real CT system (including all relevant influences on the measurement result) is necessary. Even though a measurement uncertainty determination for the end users in industry is still a topic of research, it could be demonstrated that a realistic uncertainty

determination by simulations is feasible [11, 12]. Furthermore, it was demonstrated that the single point uncertainty, divided into systematic and random deviations, can be estimated using simulations [13].
In the following, the knowledge about probable systematic deviations obtained from the simulations is used to correct the surface data obtained from a CT measurement and thus to reduce the measurement deviations of subsequent dimensional measurements. The procedure can be subdivided into four steps:

1. **Simulation:** Multiple (10) simulated measurements using a stl-file obtained from the CAD model representing the expected real measurement object are performed. For these, all parameters (e.g. magnification, X-ray spectrum, object material) are chosen as realistically as possible. The simulations are performed on the virtual metrological CT (VMCT) system representing the Werth TomoCheck 200 3D available at the institute. The VMCT has been developed in prior works at the institute [12] and is based on the software aRTist by BAM (Berlin, Germany) [7].
2. **Segmentation:** The segmentation of the simulated volume data is followed by a best fit registration against the CAD model and an export as triangulated surface file (stl). The data processing is done with the same settings as the data processing of the real measurement data lateron as those have a substantial influence on the final result (compare chapter 3). All operations were performed with VGStudio Max 3.0.1.
3. **Determination of systematic deviations:** The expected local systematic deviations are determined with an existing MATLAB algorithm for local single point uncertainties from prior works [13] (compare Figure 1). Using a remeshed CAD with significantly higher point density (compare chapter 3), the distance between the simulated surfaces and the CAD in direction of the CAD normal vector are calculated point wise for every vertex. The necessary ray tracing [14] can be implemented to efficiently use the full potential of both CPU and GPU using MATLAB. The (local) CAD normal vectors are used because measurement deviations and artefacts are expected to affect the normal vectors of the simulated surfaces. The mean of the calculated distances is the expected local systematic measurement deviation if a sufficient number of simulations is evaluated. These deviations are saved for every vertex with the CAD model.

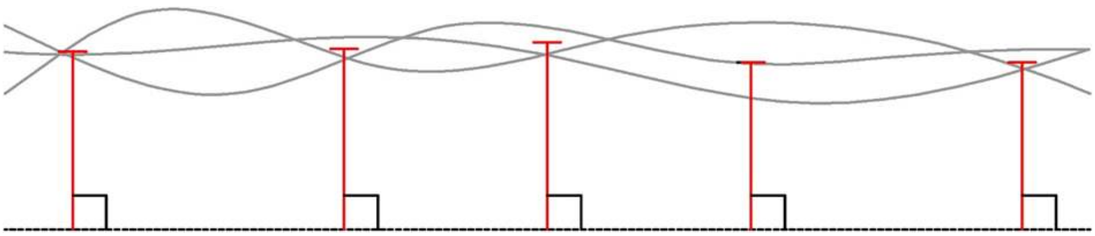

Figure 1: Sampling of the simulated surfaces (grey) with search rays (red) orthogonal to the CAD-surface (black) for the determination of the local mean deviation (systematic error).

4. **Correction of the real measurement data:** The deviation vector for each CAD point is known from step 3., but to correct the real measurement, a correction vector for each point of the segmented surface of the real measurement needs to be determined. For this purpose, for each point of the segmented surface, the point representing its shortest distance onto the CAD surface (which is not necessarily a point of the triangulation mesh) is determined. The rationale is that the closeness of the CAD surface point and the segmented surface point implies that the deviation vector of that surface point is a good estimate of the correction vector. The search for the closest point on the CAD surface resembles a ray tracing problem. The difference is that the search vector (ray direction) is not known. The problem can be simplified by implementing a spatial search routine returning the most likely solutions. There are three different possible cases:
    - Case 1: The vector to the closest point on the CAD surface is orthogonal to one of the triangles of the CAD surface and this closest point lies within that triangle (Figure 2, left). The correction vector is determined using barycentric interpolation within the triangle because the deviation vectors are only defined on the vertices of the triangle.
    - Case 2: The closest point lies on the edge of two triangles (orthogonal to that line; Figure 2, middle). The correction vector is calculated by linear interpolation between the deviation vectors of the two vertices.
    - Case 3: The closest point is a triangle vertex and the deviation vector of this vertex can be used as correction vector.

After a correction vector for each surface point of the measurement has been determined, the expected systematic measurement deviations can be compensated. Remaining deviations are caused by statistical deviations, deviations of the measured part from the CAD model and remaining unaccuracies in the simulation.
Using the correction method presented above, erroneous correction vector determinations can occur in edge regions of the part. Therefore, it can make sense to not correct the measurement in edge regions to prevent wrong ‘corrections’. For parts with clear 90° edges (compare the gauge block in chapter 3), a local neighbourhood coplanarity test can be used to identify those regions of the part. This test consists of searching all n vertex points on the reference surface in a defined neighbourhood volume around every vertex point. The coplanarity test is achieved by a singular value decomposition of the $(n+1) \times 3$ matrix of the vertex coordinates. The smallest singular value needs to be larger than a control value $\delta \approx 0$, otherwise the vertex point is not used for measurement correction. This means that any measurement point whose associated vertex point fails this test is not corrected. This simple criterion needs further elaboration for arbitrary geometries.

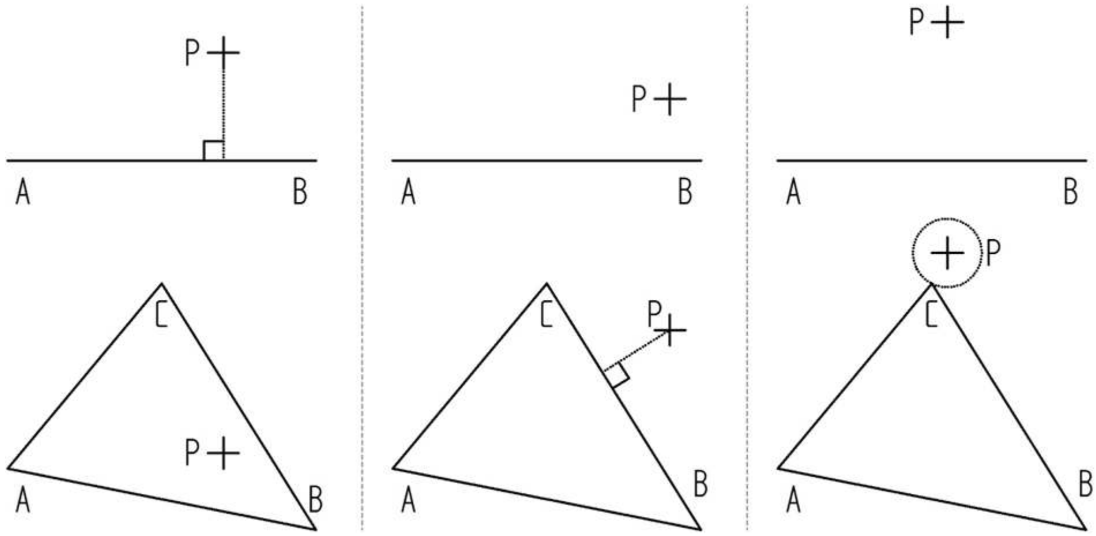

Figure 2: Illustration of the three different cases for the closest point search described in ‘4. Correction of the real measurement data’ in chapter 2. The point P is a point from the measurement surface, the triangle ABC represents the CAD surface.

Case 1 (left) is when the closest point to P on the CAD surface is within the triangle. The correction vector is calculated from a barycentric interpolation.
Case 2 (middle) shows the situation that the closest point to P is on the edge of the triangle. The correction vector is then calculated by linear interpolation from B and C.
In case 3 (right), the shortest connection of P to the surface falls onto a triangle vertex (C). The correction vector of the vertex C is used.

3 Example: Measurement of a gauge block

To test the correction method presented above, a measurement of a calibrated gauge block (steel, length 2.00 mm, width 9.00 mm, ISO 3650:1998 [15]) is used. This object was chosen because it shows two typical effects of strongly radiopaque materials: rounded edges and barrel-like distortions of planar surfaces. Gauge blocks further have the advantage of being precisely manufactured, thus the geometry is well known. The measurement was used in a prior publication [16] which already showed that disregarding surface points influenced by artefacts (identified using automated detection) can improve dimensional measurements.
The data was measured on a Werth TomoCheck 200 3D with the maximum 130 kV acceleration voltage, 16 µm voxel size and 800 projections. All known inherent correction mechanisms have been switched off. For this CT system intended for plastic part measurements, the steel penetration lengths are relatively large and significant artefacts (streaks and cupping) can thus be observed (Figure 3). These artefacts cause errors in the surface determination. The measurement object is too large for the CT used to be measured completely in one piece. Thus, only a part of the gauge block was measured.
A large dependence of the results on the segmentation parameters chosen was noted during testing. The results of a nominal-actual comparison with the CAD for automatic segmentation (VGStudio Max 3.0.1, automatic grey value threshold, search radius 8 voxels, iterative procedure, Figure 4) and manual segmentation (VGStudio Max 3.0.1, grey value threshold 35000, search radius 4 voxels, iterative procedure, Figure 5) are shown in Figure 6 and 7. The influence of the different segmentation parameters can be identified visually.

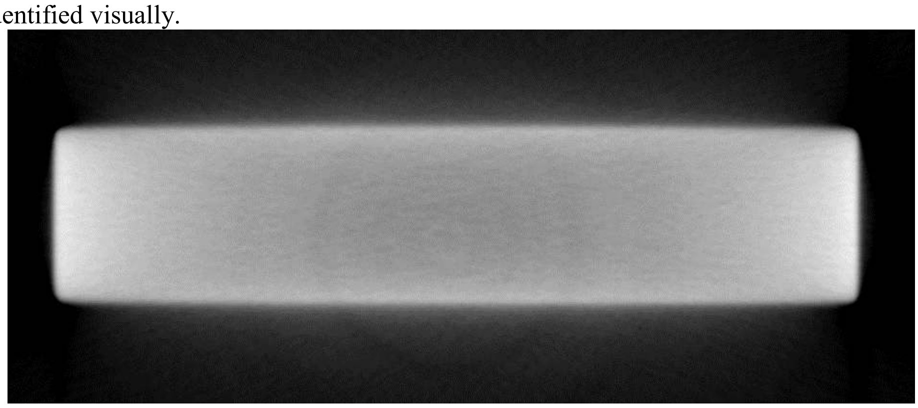

Figure 3: Cross-sectional view of the volume data of the measurement. Different artefacts which hinder segmentation and subsequent dimensional measurement are visible.

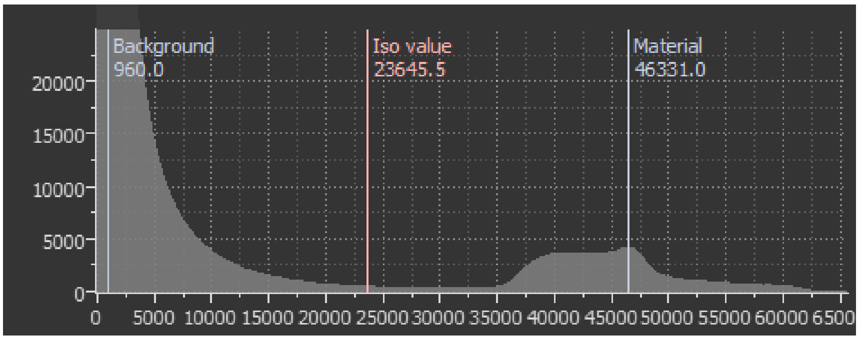

Figure 4: Automatic grey value threshold (VGStudio Max 3.0.1)

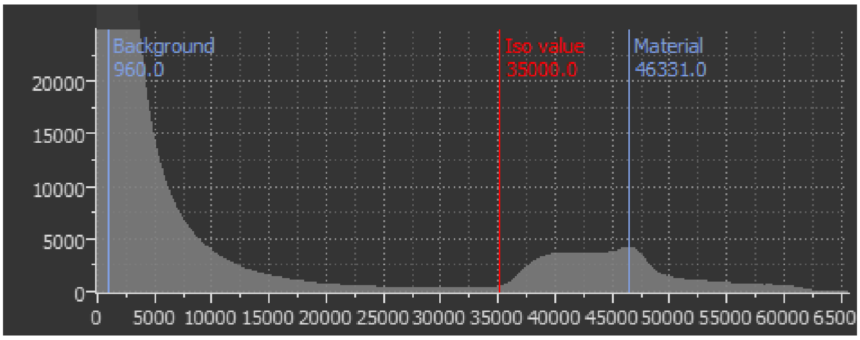

Figure 5: Manual grey value threshold (VGStudio Max 3.0.1)

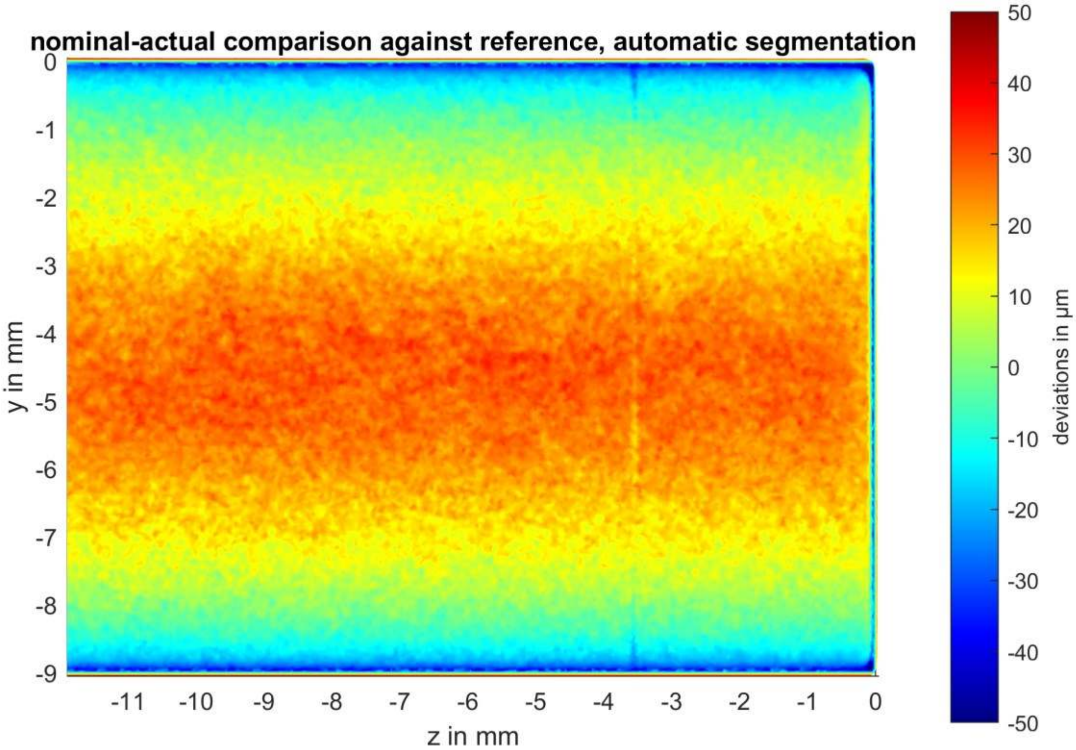

Figure 6: Nominal-actual comparison of measurement and CAD for automatic surface determination.

For the application of the correction method, the surfaces of simulated data and measured data are always determined with the same settings. In the following, only the sides of the gauge block shown in Figure 6 and 7 are evaluated as artefacts are especially severe on the side surfaces. Because of the chosen magnification and geometrical setup, the CT is just able to show a part of the full size of gauge block (20 mm x 9 mm x 2 mm), resulting in cut off plots just around 12 mm.

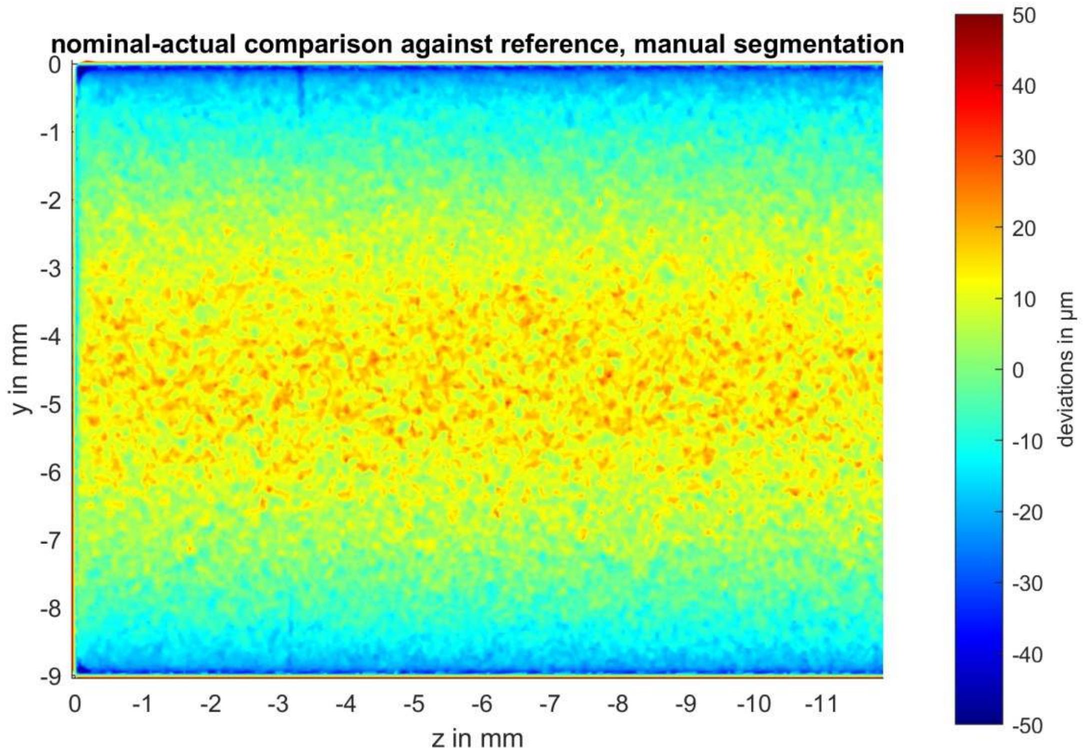

Figure 7: Nominal-actual comparison of measurement and CAD for manual surface determination.

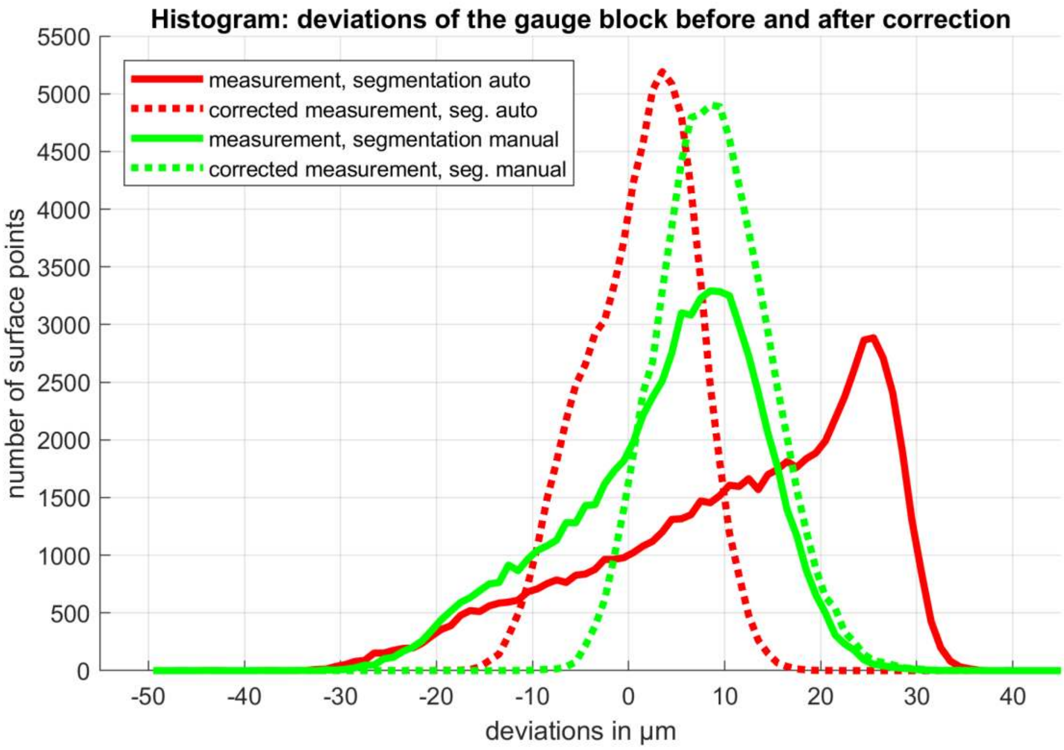

Figure 8: Histogram of the deviations on both side surfaces of the measurement from the CAD before and after correction for both segmentation methods. The point density on the surfaces is homogeneous so that the number of points corresponds to the occupied surface.

To imitate that in a real application, the actual geometry of the measured part is not known perfectly (a calibrated part is a rather theoretical case), the simulation was intentionally performed with a slightly varying geometry (length 1.95 mm instead of 2.00 mm). This means that the CAD used both for the simulation and the determination of correction vectors was smaller than the actual part. The nominal-actual comparison for the evaluation of the capability of the correction method was again performed with the original CAD to test against the actual calibrated geometry. Using a maximal point-to-point distance of 25 µm, there are about 500 000 points on the CAD surface for which correction vectors are determined with the simulated data. The real

measurement surface is then registered (least squares error function) onto the CAD surface and corrected according to the procedure described in chapter 2. The correction is not applied for points close to the edges which are determined by the coplanarity test outlined in chapter 2 using a search distance of 100 µm.
The result of the correction procedure is displayed in Figures 8, 9 and 10. The local deviations are reduced significantly for the case of automatic surface segmentation. The wave-like deviation in y-direction (Figure 9) shows that the simulated correction estimates are still imperfect, especially in the centre there is a slight over-compensation. For the manual segmentation (Figure 10), the centre area is barely corrected. There is an increase of contour accuracy in the edge areas. The strong fluctuation of deviations in the centre indicates a strong influence of statistical noise respectively an instable manual segmentation.

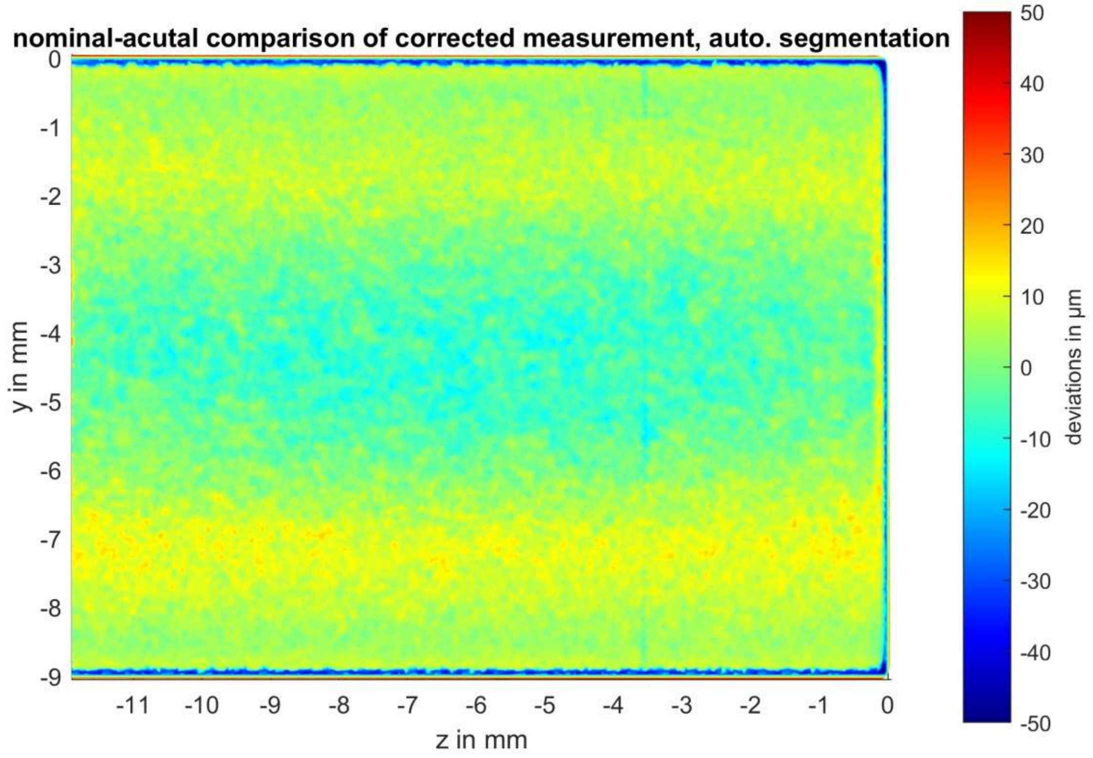

Figure 9: Nominal-actual comparison of corrected measurement and CAD for automatic surface determination.

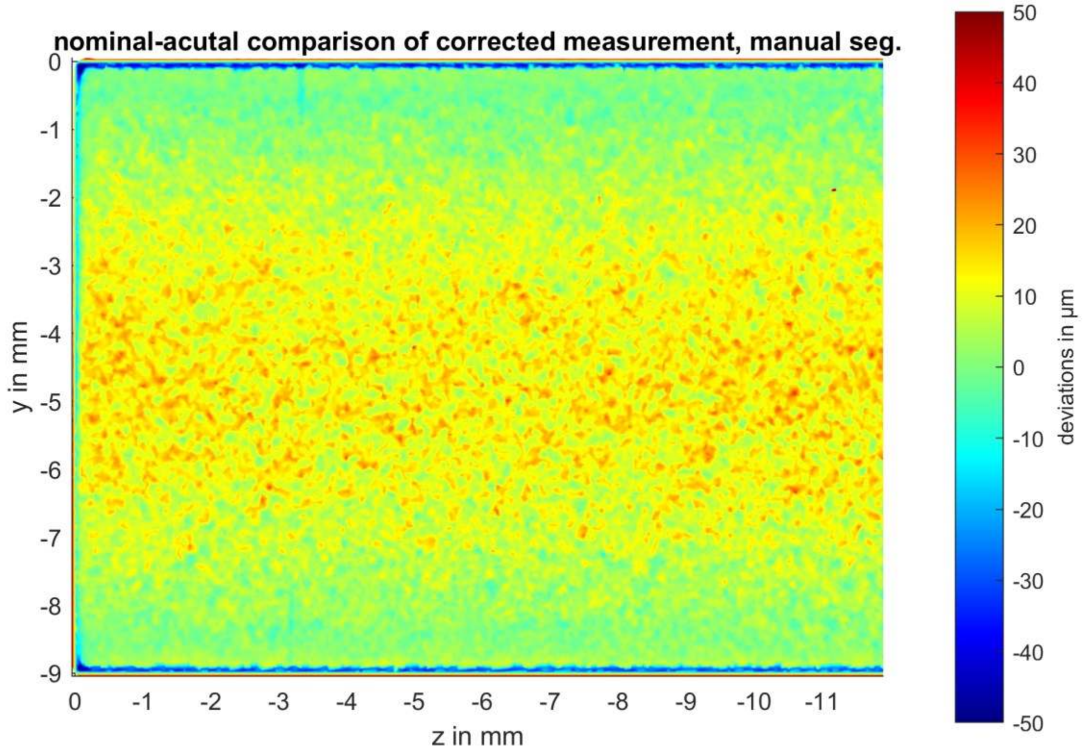

Figure 10: Nominal-actual comparison of corrected measurement and CAD for manual surface determination.

4 Discussion

The example shows that a surface correction using simulations of the measurement is possible and can reduce the measurement uncertainty of subsequent dimensional measurements. The method allows for dimensional measurement of parts which would not have been measureable without it and thus extend the range of objects for which dimensional measurements are feasible. For a further improvement of the method, an improvement of the truthworthyness of the simulation in representing the real CT system is pursued.

The method presented also has limitations. While systematic deviations can be corrected, the treatment of statistical deviations is by design not possible. Furthermore, the accuracy of the method strongly depends on the quality of the simulation data and on the ability of the simulation to reproduce real measurement data.

Like with any other correction method, a detoriation of single points is possible, i.e., a larger point-wise deviation afterwards. This is especially true of points which are correlated with the wrong region on the CAD surface. The probability for this is especially high in regions with local measurement deviations of the same order of magnitude as the local part geometry distances, e.g. at sharp edges. The problem can be minimised with the coplanarity test presented which prevents a correction of wrongly correlated points. The search radius at the edge has to be a reasonable compromise between lost correction volume and prevented ‘miscorrections’. An investigation of different correlation strategies with their simulated correction vectors is planned.

Despite these limitations, the results presented here show that the correction can provide reasonable and useful results despite certain deviations between CAD and measurement part. This is important for actual application as a calibrated part respectively a completely faithful CAD are usually not available. Despite the length difference of 1.95 mm (CAD) and 2.00 mm (measurement), a correction that reduced measurement deviations could be performed.

An advantage of the method presented here is that the extracted surface is corrected and the volume data remains unchanged. Thus, there is no risk of an unforeseen influence on the surface determination. As simulated data is used for the correction, time and machine-time consuming reference measurements are not needed. Additionally, it is possible to correct internal geometries for which a nondestructive reference measurement might not be possible. The correction is not limited to a special type of artefact but can correct all systematic deviations that the simulation can reproduce.

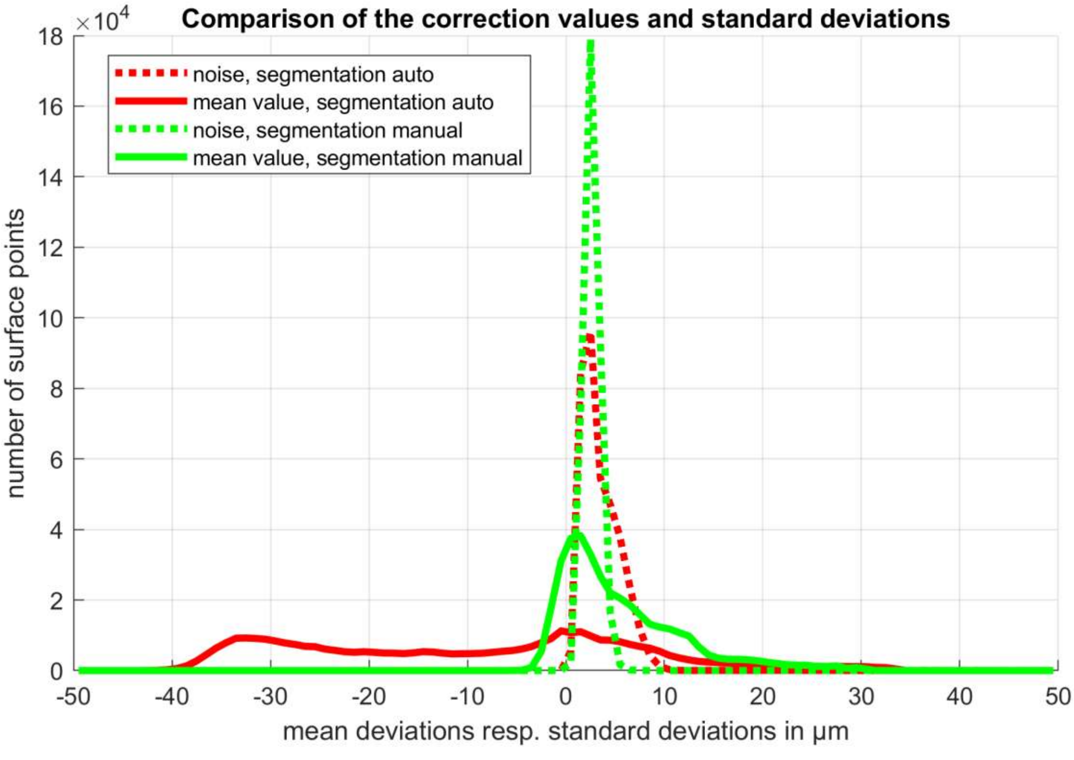

Figure 11: Histograms of the magnitude of the correction vector (with the sign indicating ‘in the direction of’ or ‘in the opposite direction of the normal vector’) (lines) and its standard deviation (dotted lines) for both segmentation modes in comparison.

It could be shown that the choice of segmentation parameters influences the dimensional measurement. A manual choice of parameters reduced the observed deviations before correction significantly. The corrected surfaces are quite similar for both segmentation modes near the edges but the centre is overcompensated for the automatic segmentation and not compensated sufficiently for the manual segmentation. A further comparison of the two segmentation routines is shown in Figure 11. It can be seen that the mean correction vector magnitude is larger for the automatic segmentation than for the manual segmentation. The difference in the noise is smaller in comparison, thus the signal to noise ratio for the correction vectors in the case of manual segmentation is worse. Consequently it is probable that the correction method works better in cases where there are relatively pronounced local artefacts leading to systematic deviations significantly higher than statistical deviations.

The method as presented here was applied to an uncorrected measurement. It is by design possible to combine the method with any other correction method (e.g. beam hardening correction). In this case, the application of the other correction method to the simulated data would allow to compensate any remaining systematic deviations not corrected by the other method (e.g. cone beam artefacts). Therefore, the method presented here can serve as a useful addition to established correction methods.

5 Conclusion

A new approach to correct systematic deviations in real CT measurements by predicting the expected local deviation using simulations has been presented. Results using the measurement of a steel gauge block have been presented. The results show a strong dependence on the segmentation settings. Independent of the segmentation settings, the new method achieves a significant reduction of measurement deviations in the edge regions of the measurement object. Though the centre area is slightly overcompensated for, an overall improvement of the surface can still be achieved. Based on the promising results presented in this work, an improvement of this method by an optimised simulation and optimised segmentation settings seems possible. A further reduction of the correction vector noise should be achievable by increasing the number of simulations and seems advisable due to the signal to noise ratio.
Especially for strongly radiopaque materials, the large amount of influencing factors causes significant measurement deviations, which limits the applicability of CT systems. Using appropriate correction algorithms like the one presented in this work, these deviations can be reduced and the applicability of the CT system can thus be extended significantly.

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