Improving geometry element regression analysis for dimensional X-ray computed tomography measurements using locally determined quality values

Andreas Michael Müller¹ and Tino Hausotte¹

¹Institute of Manufacturing Metrology (FMT), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Nägelsbachstr. 25, 91052 Erlangen, Germany, e-mail: {andreas.mueller | tino.hausotte}@fmt.fau.de

Abstract
X-ray computed tomography (CT) enables the determination of numerous dimensional measurands with a single scan. However, measurements are often affected by artifacts, which are mainly caused by the effects of the complex physical interactions between the used radiation, the measurement object and the detector as well as the algorithms used for measurement data processing. Surface regions affected by artifacts lead to an inaccurate surface determination and therefore to increased measurement deviations and uncertainties of geometric measurements. This contribution aims to demonstrate the possibility of detecting negatively affected surface regions by a qualitative examination of the underlying volume data in the region of each determined surface point. This classification is used to improve different kinds of sphere measurements, which are evaluated by performing regression analysis onto the measured point clouds. Because of the available qualitative classification for each surface point, it is possible to apply a suitable weighting metric before applying the regression analysis in order to reduce the influence of lowly classified surface areas onto the measurement result. The workflow is demonstrated with a calibrated multi-sphere specimen. The results show that a significant reduction of the measurement errors associated with the evaluation of sphere centre distances, sphere form and radius deviations, respectively, can be achieved, while using the regression analysis tools of the commercial software VGStudio Max (Volume Graphics GmbH).

Keywords: dimensional metrology, regression analysis, surface point quality, measurement uncertainty

1 Introduction

Using coordinate measuring technology, the geometry of work pieces can be validated against the specification of the design engineer. The shape of work pieces is described by standard geometry elements (e.g. point, straight, circle, plane, sphere, cylinder, cone, torus) and freeform surfaces, which position and orientation are dimensioned and tolerated in accordance with the principles of the Geometrical Product Specifications (GPS) [1]. The GPS defines the association operator, which is used on geometric elements to adjust ideal geometry elements to non-ideal elements (represented by measured coordinates) according to specific criteria. Mathematically, this operation is described by a regression analysis, also called “fit” or “fitting”. The effects of various error sources affect every real measurement, which leads to imperfect information about the examined measurement object. In metrology, measurement uncertainty is the expression of the statistical dispersion of the values attributed to a measured quantity [2]. For X-ray computed tomography (CT), the local measurement uncertainty associated with the edge points defining the reconstructed surface of the measurement object is varying depending on the measurement setup [3]. We could show in previous works, that the evaluation of the CT volume data in the vicinity of a determined surface point can be used to obtain a quality parameter for that surface point [4–6]. Additionally, this (quality) parameter could successfully be implemented as weighting factor for an iterative surface data fusion routine [7]. Other authors published similar approaches for the determination of pointwise defined surface quality parameters [8, 9].

This contribution aims to demonstrate possible improvements for the evaluation of standard geometry elements for CT measurements by the specific selection of fit points within the data processing pipeline of Volume Graphics VGStudio Max (VGS) using locally determined surface point quality values. CT measurements of a calibrated artefact surrounded by additional high-density disturbing bodies were performed and the regression results using the unaltered fit points and selected fit point based on their surface point quality value were compared against each other. The observations show that significant improvements were made for all examined measurands (sphere centre distances, sphere form deviations and sphere radii) for the demonstrated measurement task. Thus, the suitable integration of the surface point quality values leads to a substantial reduction of the measurement uncertainty of CT measurements for the demonstrated use cases.

2 Determination of the surface point quality (SPQ) [10]

The presented research is based on the assumption, that there exists some kind of exploitable correlation between the metrological correctness of a CT surface point and its associated “surface point quality” (SPQ). Consequently, an improvement of a dimensional measurement is in principle possible, if surface points classified as “bad” can be treated differently than those points with a “good” classification. This section briefly describes the used methodology to evaluate the SPQ of a CT measurement. The approach aims at calculating a quality parameter for every discrete surface point of the determined surface. This parameter can then be used to compare surface points with regard to their quality (e.g. caused by local CT-specific measurement artefacts) and subsequently provide the possibility of selective data processing during the evaluation of a measurement result. The main idea

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is to evaluate the CT volume data in form of the grey value transition in the proximity of the determined surface of the measurement object. Including knowledge about the physical principles of CT as well as the underlying mathematical models and algorithms, the SPQ allows the determination of sophisticated quality parameters, which are capable of detecting subtle fluctuations in the examined grey value transitions.

Firstly, a CT measurement is recorded and the result of the following surface determination is exported as a triangulated surface in the STL file format. Then the vertex normal vectors are calculated, following the convention that the direction of the vector is outward. Knowing the coordinate transformation between surface data and volume data, for each surface point (here unique triangle edge point), the grey value profile in the direction of the corresponding vertex normal vector can be sampled (Fig. 1). This profile is centred with regard to the surface point location and typically has a user defined (unidirectional) length of 4 to 15 voxels. The x-axis (position along the sampling vector) is counted positively in the direction of the vertex normal vector. The derivatives of the sampled grey value transitions are strongly affected by the fact that the volume data are gridded data (discrete). Suitable application of additional smoothing of the grey value profile (e.g. spline filter) can reduce these effects.

![Exemplary grey value transition for a surface point](image)

Figure 1: Grey value transition of a single surface point with gradient and curvature

The local differences of the SPQ represent local changes of the volume data in the proximity of the work piece boundary and can therefore indicate surface regions with a potentially increased determination uncertainty. The mathematical criteria for the evaluation of grey value transitions include but are not limited to the following examples:

- value and location of the maximum gradient, width of the gradient curve,
- value of the maximum absolute curvature, locations of zero crossings of the curvature,
- symmetry of the transition with respect to the underlying surface point location,
- contrast and monotonicity of the transition,
- grey values at each end of the sampling length with respect to the maximum / minimum grey value,
- local statistical behaviour of the aforementioned criteria.

The evaluation of the SPQ then takes place by comparing all surface points of the complete dataset using false-colour plots with suited colour maps. Nonetheless, the main challenges associated with this method are the abstract nature of the determined quality parameters and the requirement of expert knowledge in the field of CT in order to explain the origin of detected artefacts.

### 3 Measurement task and data processing pipeline

The used measurement object is the Zeiss Metrotom Check artefact, which consists of 27 spheres (Ø5 mm). The artefact was scanned using the CT system Zeiss Metrotom 1500G2 with two different measurement configurations (Tab. 1).

<table>
<thead>
<tr>
<th>Setting</th>
<th>Unit</th>
<th>CT configuration 1</th>
<th>CT configuration 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray tube voltage</td>
<td>kV</td>
<td>112</td>
<td>225</td>
</tr>
<tr>
<td>X-ray tube current</td>
<td>µA</td>
<td>888</td>
<td>111</td>
</tr>
<tr>
<td>Nominal X-ray spot size</td>
<td>µm</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>X-ray source power</td>
<td>W</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>integration time</td>
<td>ms</td>
<td>500</td>
<td>267</td>
</tr>
<tr>
<td>X-ray pre-filtration</td>
<td>-</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>detector gain</td>
<td>-</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>geometrical magnification</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>resulting voxel size</td>
<td>µm</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>number of projections</td>
<td>-</td>
<td>1500</td>
<td>1500</td>
</tr>
</tbody>
</table>

For each configuration, the measurement object was scanned with and without six additional disturbing bodies made out of aluminium and steel (Fig. 2), in order to provoke potential measurement errors, which can then be corrected using weighted fit points. The reconstructed volume was processed using VGS 3.2.5. The surface determination was performed using the default
advanced settings, with “remove all particles and voids” enabled. Three different geometrical features of spheres were determined and compared against their respective reference value (Tab. 2).

Table 2: Evaluated measurands

<table>
<thead>
<tr>
<th>Measurand type</th>
<th>Number of measurands</th>
<th>Reference value</th>
</tr>
</thead>
<tbody>
<tr>
<td>sphere centre distance deviation</td>
<td>35</td>
<td>CMM calibration, U = 1.0 µm [11]</td>
</tr>
<tr>
<td>sphere form deviation</td>
<td>27</td>
<td>0.0 µm (nominal value)</td>
</tr>
<tr>
<td>sphere radius deviation</td>
<td>27</td>
<td>2.5000 mm (nominal value)</td>
</tr>
</tbody>
</table>

Figure 2: Zeiss Metrotom Check artefact (27 spheres) with disturbing bodies (4 times aluminium, 2 times steel)

Figure 3: Volume data slice through a measurement with disturbing bodies (CT configuration 1). The contrast was adjusted manually to highlight the streak artefacts present.

Figure 4: Classification of the SPQ of all fit points (Chebyshev, exported from VGS). Green colour represents higher quality; red colour represents lower quality, respectively.

The complete data processing pipeline consists of the following chronological steps:
- Record the mentioned CT measurements and perform the surface determination (VGS) as described above. An exemplary volume data slice is shown in Fig. 3.
- For each measurement and each measured sphere, perform manual sphere fits (VGS) using the default settings with the adjustments “Point creation: Smart expand” and “Sampling options: Step width [mm]” set to zero (this ensures the full...
amount of fit points is created, here 1000). This step is performed using the four different fit methods “Gauss (least squares)”, “Chebyshev (minimum zone)”, “Minimum circumscribed” and “Maximum inscribed”.

- Export the fit points from VGS.
- For each single sphere measurement, calculate the SPQ for each fit point (coordinates and virtual probing vector are given by the VGS export) using a suitable performance metric. For all measurements and regression methods, the same SPQ method was used. A false colour plot is shown in Fig. 4.
- Depending on the property of the used metric, remove those fit points from all fit points describing that sphere $SPQ_{sph}$, whose value is smaller/larger than the median value of $SPQ_{sph}$ minus/plus the standard deviation of $SPQ_{sph}$ (1).

"larger" SPQ is “better”: remove fit point if: $SPQ < \text{med}(SPQ_{sph}) - \text{std}(SPQ_{sph})$

"smaller" SPQ is “better”: remove fit point if: $SPQ > \text{med}(SPQ_{sph}) + \text{std}(SPQ_{sph})$

- Import the modified fit points back into VGS and repeat the fit routine with modified settings “Point creation: Single point”, “Fit point filter options: Iterations 0” as well as the disabled setting “Options: Snap fit points to surface before starting iterations”.
- Generate a CM report containing all fit results and compare the results for the different CT configurations, measurands, and fit methods.

4 Results

The results of the described setup are visualized in Fig. 5 and 6. Each plot shows the statistical evaluation of the deviations of the different measurands from the corresponding reference values. The used naming convention for the examined measurands is described in Tab. 4.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPH-DST</td>
<td>Sphere centre distances, n = 35 (see also Tab. 2)</td>
</tr>
<tr>
<td>FRM-DV</td>
<td>Form deviations, n = 27 (see also Tab. 2)</td>
</tr>
<tr>
<td>RD-DV</td>
<td>Radius deviations, n = 27 (see also Tab. 2)</td>
</tr>
<tr>
<td>M (boxes in red colour)</td>
<td>Measurement with disturbing bodies</td>
</tr>
<tr>
<td>C (boxes in green colour)</td>
<td>Corrected measurement result of M using SPQ regression</td>
</tr>
<tr>
<td>R (boxes in blue colour)</td>
<td>Reference measurement without disturbing bodies</td>
</tr>
</tbody>
</table>

Table 4: Used naming conventions for the result box plots in Fig. 5 and Fig. 6

Figure 5: Statistical evaluation of the observed measurands for CT configuration 1. See also Tab. 4 for further explanations.
5 Discussion

For all observed form and radius deviations respectively, the introduction of the SPQ to the used regression analysis leads to an improvement of the measurement result. Thus, it is obvious that the applied correction procedure is able to reduce the measurement uncertainty. Examining the sphere distances, improved results were achieved for fitting methods “Chebyshev” and “Minimum circumscribed” (GC / GN) for both CT configurations, with the results being inconsistent for both remaining regression methods. Surprisingly, the regression analysis using the SPQ could obtain even better results than the unobstructed measurement, when observing the radius deviations for fit methods “Gauss” (GG) and “Chebyshev” (GC), independent of the used CT configurations. The observed results are consistent between both CT configurations, which means that even though the measured deviations differ slightly, the general correlation between the SPQ and the dimensional correctness of the measured surface point remains unaffected by different CT configurations.

6 Summary and outlook

This contribution demonstrated a methodology for a potential reduction of the measurement uncertainty for CT measurements. Here, the main idea was to identify surface regions affected by artefacts using the SPQ method and subsequently remove bad points from the regression analysis (fitting). The approach was validated using a calibrated sphere artefact, where sphere centre distances, sphere form deviations and sphere radius deviations were examined. The data processing was performed based on the commercially available software VGS.

The results show that a significant reduction of the observed measurement error was achieved by filtering the fitting points based on their SPQ, compared to the unaltered measurement.

The main challenge using this method is that the SPQ is an abstract value and thus it is unclear, which or how many fit points should be filtered out in order to achieve the best result. In this contribution, a statistical measure was chosen (1), which could arguably not produce optimal results for all use cases. Secondly, an approach where fit points are weighted continuously as opposed to a binary weighting could potentially further improve the results.

Acknowledgements

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