Parameter Dependent Thresholding for Dimensional X-ray Computed Tomography

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Abstract. While computed tomography (CT) has since long been used for medical applications and material inspection, its application field has recently been broadened to include dimensional metrology in industry. However, the accuracy and repeatability of CT-based measurements remain yet largely uncertain. Not only are the measurements influenced by a number of factors and parameters like e.g. voltage, current, magnification, object thickness, but also the calibration method is of major concern (both for scale errors as well as for offset errors).

This paper investigates the influence of the power settings (voltage and current) on the accuracy and repeatability of dimensional measurements. Experiments show that after rescaling the pixel size (to compensate for scale errors), the accuracy still remains dependent on the energy used. After correction of the edge threshold value (offset error), measurement results become less dependent on the voltage and current used and are more repeatable.

Beam hardening effects cause the material thickness of the measurand to be another important parameter. Using spheres of different sizes, the dependence of the edge offset error on the sphere diameter is investigated.

1. Introduction

Computed tomography (CT) is well known from medical applications. In addition, CT machines have been used in industry for material inspection and qualitative quality control for several decades. Since a few years, the application field has been broadened to include dimensional metrology. This application field gains interest, since until now CT is the only way to measure internal structures and complex objects in a non-destructive way. However, the accuracy and repeatability of CT measurements is dependent on a variety of parameters and remains yet largely uncertain. Besides hardware (spot size, detector pixel size, ...) and software (reconstruction algorithm, beam hardening correction algorithm, ...), also the workpiece itself (material, size, ...) will determine the accuracy of the measurement [1].

The influence of several parameters on the accuracy and repeatability of dimensional measurements has been investigated by simulation [2,3] or experimentally [4,5,6]. This paper concentrates on the influence of power settings (voltage and current) and material thickness. In addition, the sensitivity of the conclusions to machine hardware (detector sensitivity) and data analysis procedure (thresholding method) is briefly discussed.

2. Measurement equipment, software and procedure

The first step in a CT measurement is the acquisition of the data. Some hundreds or even thousands of 2D X-ray images are taken from the object in different orientations. The specifications of the X-ray source of the CT device used are summarized in Table 1.

Table 1. Specifications of the CT-devices used

Source	Micro focus source (5µm focal spot size) Max. voltage = 225 kV Max. Current = 2000 µA
Varian Detector (Figure 3,4,8)	1916 x 1536 pixels Pixel size: 127 x127µm
Perkin Elmer Detector (Figure 6,7,9)	1024 x 1024 pixels Pixel size: 400 x400 µm

Subsequently, the 2D X-ray images are reconstructed into a 3D voxel model. Optionally, beam hardening correction or noise reduction algorithms can be applied to improve the visual quality of the voxel model, although it remains uncertain to what extent they also improve the dimensional accuracy. The results presented in this paper are based on reconstructions obtained using the CT-Pro software, and illustrate both the use of a linear beam hardening correction algorithm and the use of data without beam-hardening correction.

Further data processing of the voxel model has been performed in VG Studio Max. A reliable calibration for the voxel size (rescaling) and a correct edge detection are essential steps in the measurement procedure for accurate dimensional measurements with CT.

First, one has to define the edge between the background and the material pixels: the surface of the object model. Commonly, the 50% iso-surface is determined, considering one gray value (halfway between the peak for the background and the peak for the material on the measurement gray value histogram) as a global threshold value (global thresholding). Other methods define the threshold value locally by looking for e.g. the highest grey value gradient (local thresholding). The accuracy of the edge detection is directly related to the accuracy of the measurements. The influences investigated in this paper are illustrated with examples using both types of thresholding methods.

Besides edge detection, a voxel calibration step is needed to define the size of the voxels in the model. The closer the object is to the source, the higher the magnification and the smaller the voxel size. However, using the position along the magnification axis as a reference for calibration is not always sufficiently accurate. A number of calibration objects have been proposed to rescale for the correct voxel size and for determining the edge threshold value [7,8,9]. The experiments described in this paper use edge-independent distances (e.g. the distance between center points of two spheres) in order to perform voxel calibration. The rescale factor RS for the voxel size is then calculated as:

$$\mathrm{RS} = \frac{\mathrm{Ref}_{a,b}}{\mathrm{CT}_{a,b}}$$

where $\mathrm{CT}_{a,b}$ represents the edge independent distance on the voxel model whereas $\mathrm{Ref}_{a,b}$ represents the reference value for this distance measured using e.g. CMM or guaranteed by the manufacturer. The reference distance is taken as large as possible in order to reduce the influence of random or residual systematic errors on the magnification factor. All results reported in this paper are values after rescaling. The uncertainty on the results caused by the rescaling method is estimated to be ca. 0.1%.

3. Influence of X-ray source settings (voltage and current)

The settings of the X-ray source (voltage and current) are typically defined using some rules of thumb. The voltage must be sufficient to penetrate the workpiece in each orientation; the current is chosen in order to maximize the contrast of the images without saturating the background. Within these limits, different combinations of voltage and current are possible. The final selection of the settings is strongly dependent on user preferences. This section investigates whether a significant difference can be found between the allowable settings.

Test object 1: cactus step gauge

The first test object is an aluminium cube (45x45x45 mm) with parallel through grooves in the shape of a "cactus" (Figure 1). The planes are numbered (1 to 8) and divided in different zones (A to F). The distance between two successive planes is 5 mm. The measured features reported on in this paper are the horizontal distances between the planes in zone D.

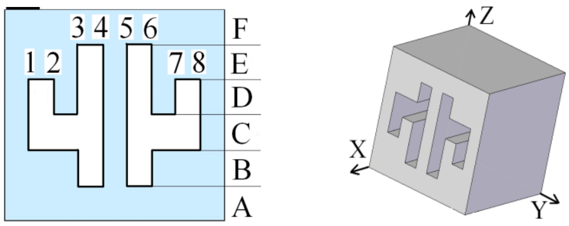

Figure 1. Front view and 3D model of the cactus step gauge [10]

Since the walls in this zone all have equal material thicknesses, no size influences (cf. Section 4) are expected. In addition, the geometry of the test object allows for both voxel calibration based on edge independent distances (Figure 2b) and edge offset determination based on edge dependent distances (Figure 2a) [10].

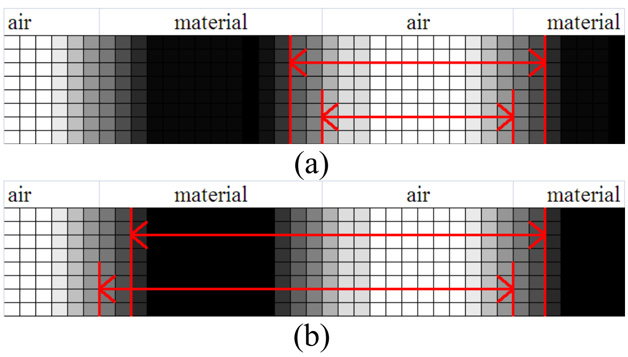

Figure 2. Edge dependent (a) and edge independent distances (b)

The cactus step gauge has been measured with 13 different settings, using a CT-device with a Varian 2520 detector. Maximum gradient based local thresholding in combination with a linear beam hardening correction algorithm has been used for the voxel model reconstruction. All 5 mm distances between adjacent planes on the model in zone D are measured and rescaled based on an edge independent distance; in order to minimize rescale factor induced errors, the average of distances 1-7 and 2-8 has been used to determine RS. The differences between the rescaled CT measurements and the CMM reference measurements are shown in Figure 3. The figure shows that the deviations are dependent on the voltage and current settings used: higher settings imply larger deviations.

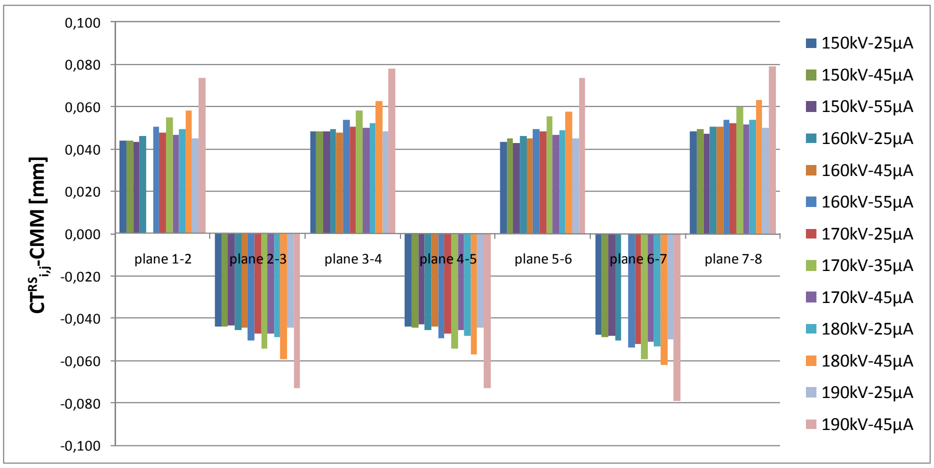

Figure 3. Deviations between the rescaled CT values and the CMM reference measurements for different voltage and current settings (local thresholding, linear beam hardening correction)

Figure 3 moreover shows that there is a significant edge offset error: on the CT model, air gaps are too wide, whereas walls are too thin. Therefore, the results of each measurement are corrected using the distance 4-5 as a setting-dependent correction term, following the method proposed by Kiekens et al. [10]:

$$CT_{i,j}^{Corr} = CT_{i,j}^{RS} \pm (Ref_{4,5} - CT_{4,5}^{RS})$$

where $\mathrm{CT}_{i,j}^{\mathrm{RS}}$ and $\mathrm{CT}_{i,j}^{\mathrm{Corr}}$ represent respectively the rescaled distance between plane *i* and plane *j* before and after edge correction, and $\mathrm{Ref}_{4,5}$ represents the distance between planes 4 and 5 measured by CMM. The distance used for edge correction is preferably a small one in order to reduce the influence of residual scaling errors on the edge correction term.

After edge offset correction, the deviations are reduced to levels within the uncertainty limits of the CMM measurements (Figure 4). Furthermore, no significant differences or trend remains between the results obtained with different settings. Hence, a reliable edge correction method seems to eliminate the setting dependency of the measurement accuracy and to improve the repeatability.

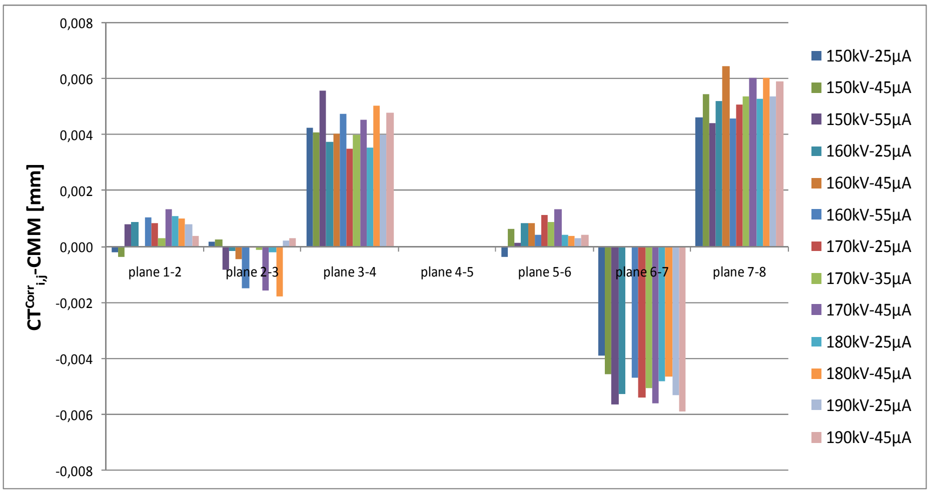

Figure 4. Deviations between rescaled CT values after edge correction and the CMM reference measurements for different voltage and current settings; notice the scale difference with Figure 3

Test object 2: chrome steel spheres

Since both the material and the shape of the measurand are important parameters in CT (e.g. a flat plane causes more scatter and diffraction than a sphere), a second experiment was performed on a test object consisting of chrome steel spheres: 8 touching spheres of diameter 3mm and 9 touching spheres of diameter 6mm (Figure 5). The spheres are inserted in cylindrical holes drilled into a polymer carrier. All spheres have an accuracy of ± 2µm on the diameter. Notice that also this test object comprises edge dependent distances (the diameters of the spheres) and edge independent distances (the distance between the centre points of two adjacent spheres).

The CT images of the bottom spheres were influenced by the presence of thicker carrier material. In addition, deviations were observed at the top spheres due to the non-symmetrical situation. Therefore, the results are based only on the middle spheres (marked by the red rectangles in Figure 5).

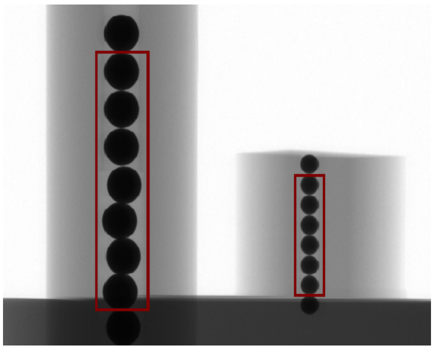

Figure 5. Test object with chrome steel spheres

The measurements of this second test object are performed using a similar source as above, but with a Perkin Elmer 1621 detector.

The diameters of the spheres were measured with 5 different combinations of voltage and current and rescaled using the distance between the center points. Figure 6 shows that the deviations are once more dependent on the settings used. The dependence of the deviations on the settings is found for global thresholding based on the 50% iso-surface, as well as for local thresholding. In addition, the setting dependence is observed irrespective of the use or absence of beam hardening correction (Figure 7). Nevertheless, one notices that the magnitude and even the sign of the recorded deviations are strongly dependent on the applied data processing algorithms.

Since six 3mm spheres and seven 6mm spheres were measured in test object 2, the error bars on Figures 6 and 7 indicate the ranges measured for each diameter. These ranges give an indication of the repeatability of the measurements and of the accuracy that can be reached when applying a correction term similar to the procedure followed for the cactus gauge block. It is clear that applying a settings dependent edge correction term can improve the accuracy of the measurements significantly, and will largely eliminate the influence of the settings.

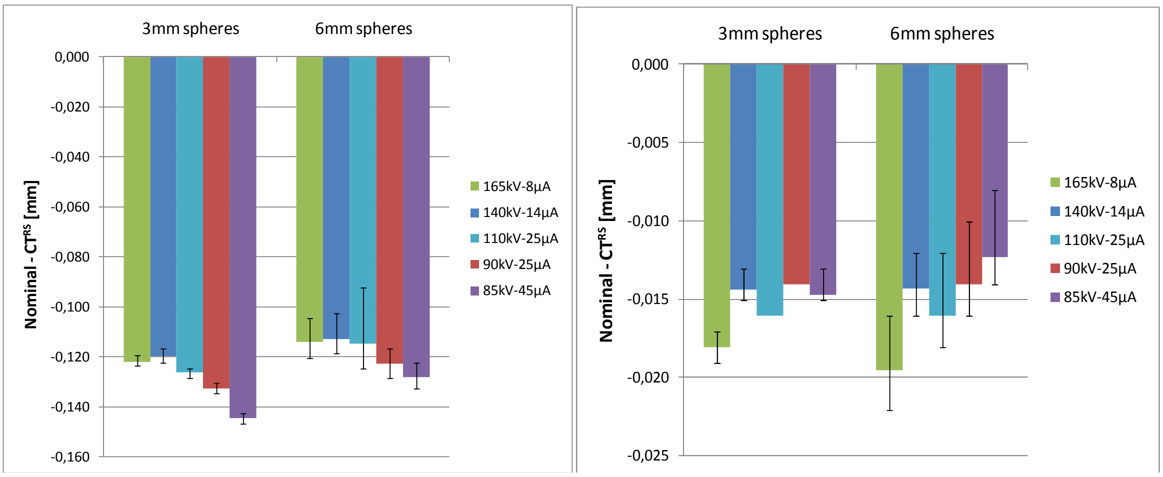

Figure 6. Deviations between the rescaled CT values and the nominal reference values of the sphere diameters for different voltage and current settings for global (left) as well as for local (right) thresholding

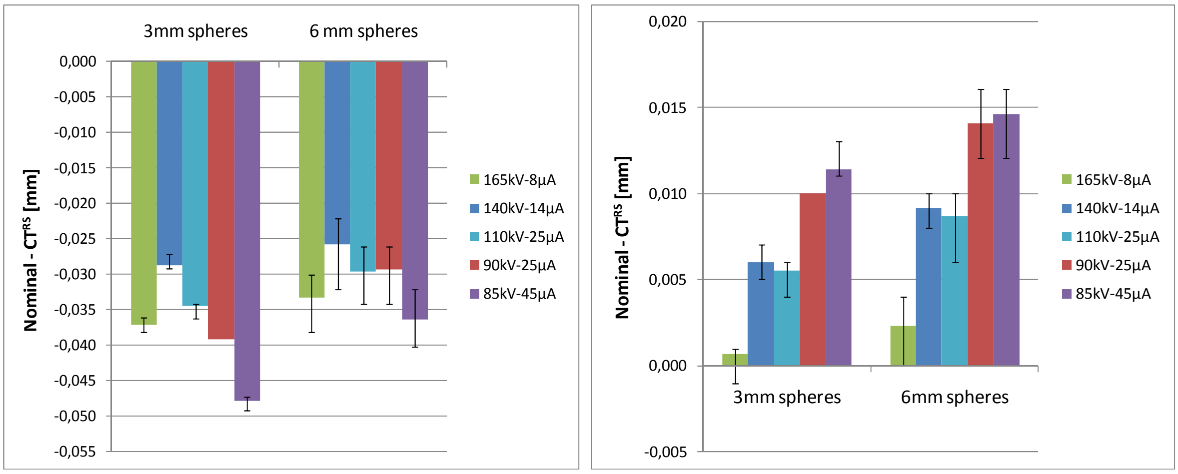

Figure 7. Deviations between the rescaled CT values and the nominal reference value of the sphere diameters for different voltage and current settings for global (left) as well as for local (right) thresholding, using a linear beam hardening correction method in the reconstruction step

4. Material thickness

The results presented in Section 3 indicate not only setting influences, but also influences of the object’s material thickness: spheres of 3mm and of 6mm yield different deviations. Therefore, this section presents analyses of measurement series using test objects comprising multiple spheres with varying diameters. Measurement results from two different machines featuring different detectors are presented and briefly compared.

Test object 3: five chrome steel spheres

The *first set-up* consists of 5 spheres with nominal diameters ranging from 1 to 5 mm (Figure 8, left). The spheres are mounted in light polymer foam. This object was measured on a 225kV machine, with a Varian 2520 detector (170kV – 45µA). The rescaling (voxel size calibration) was done by measuring a calibration object, consisting of two ruby spheres at a known distance from each other. The measurement has been reconstructed without beam hardening correction. After rescaling, the deviations tend to increase with increasing diameter. Results are shown for local thresholding as well as for different global thresholding strategies.

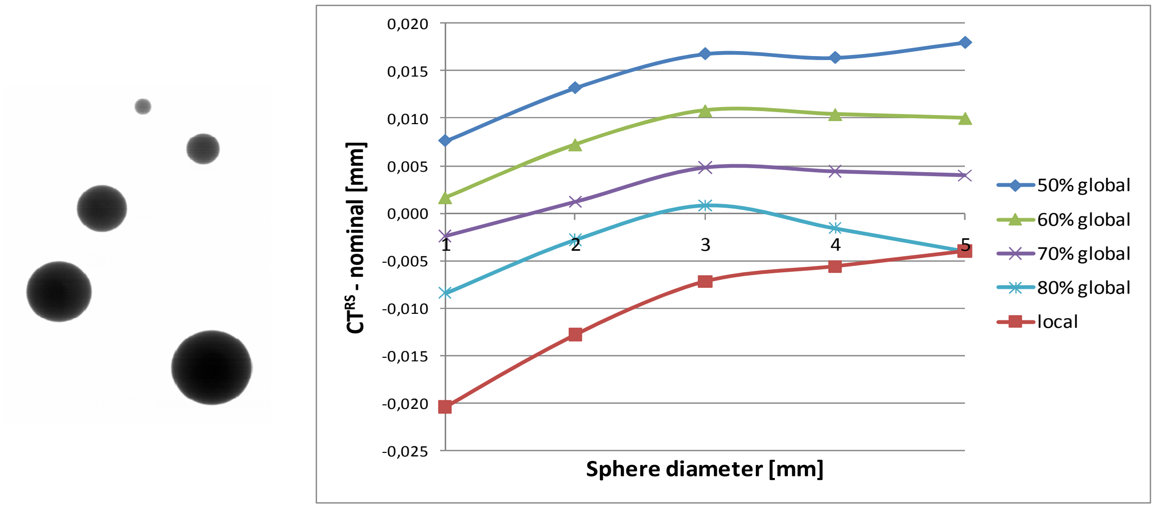

Figure 8. Left: Set-up with five chrome steel spheres with different sizes (diameters from 1 to 5 mm); Right: Deviations between rescaled CT values and the nominal value for spheres with different diameters measured with Varian 2520 detector

Test object 4: ten chrome steel spheres

A last set-up consists of a wider range of diameters, now between 1 and 10 mm (Figure 9, left). This setup was measured on a different 225kV machine, with the same source, but with a Perkin Elmer 1621 detector (138kV – 15µA). For rescaling of this voxel model, the distance between two adjacent spheres of 3 mm diameter, measured in the same set-up and visible on the right hand side of the image has been used. Similarly to the previous measurement, no beam hardening correction has been used.

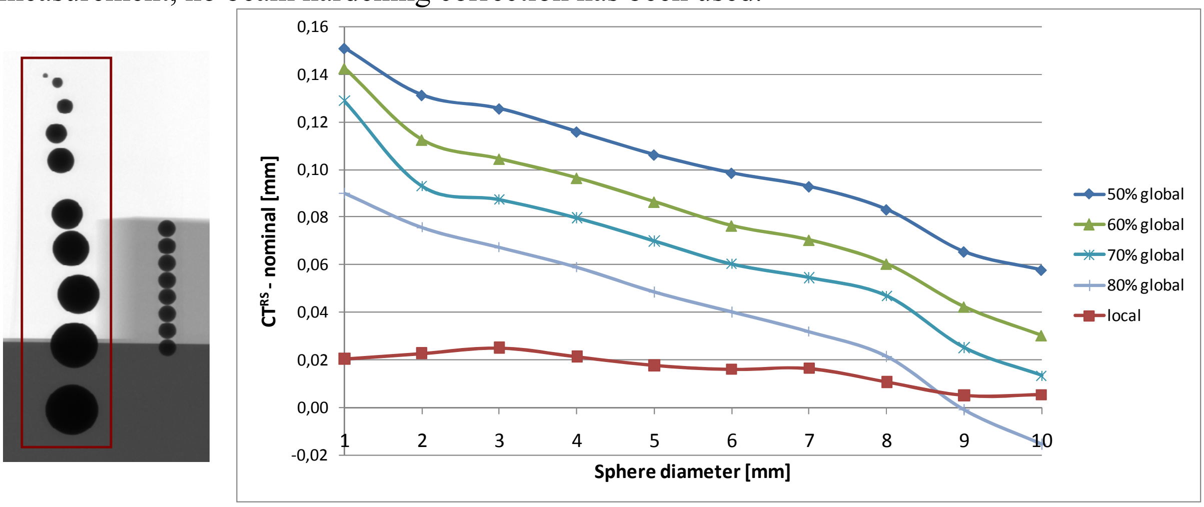

Figure 9. Deviations between rescaled CT values and the nominal value for spheres with different diameters measured with Perkin Elmer 1621 detector

Discussion

The results of the experiments above indicate that, within a certain diameter range, a nearly linear relationship between the diameter and the errors remaining after rescaling is apparent. The slope of the curve is, however, different for both measurements and seems to depend on thresholding method, machine (detector), beam hardening correction, filtering, … However, it is apparent that the correct threshold value depends on the material thickness. The only exception is the result of the second measurement after local thresholding, where the deviation seems to vary only very slightly.

5. Conclusion

This paper shows results of experiments investigating the influence of settings and object thickness on the accuracy of CT measurements. The results confirm once more that many different factors influence this accuracy, and that mutual interaction between these factors is present.

The results obtained using a cactus step gauge show that the CT deviations are dependent on the source settings. After applying a settings dependent edge correction, the accuracy and repeatability of the measurements however improves significantly. The need for a settings dependent correction term is confirmed in experiments using steel spheres. In addition, this conclusion proved true irrespective from the applied edge detection (50% iso-surface global or local thresholding) and beam hardening correction methods (with or without edge correction). Nevertheless, the magnitude and sign of the required edge correction term is different for different combinations of those parameters.

Subsequently, the influence of the material thickness on the CT accuracy was investigated using two set-ups of accurate spheres with different diameters. Both measurements confirm that the deviations after rescaling are size dependent and a linear relationship between deviation and size can be observed. The slope of this curve is, however, dependent on other parameters.

The investigations hence lead to the conclusion that a correct edge determination should be dependent on the machine settings used as well as on the material thickness.

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