Self-calibrating helical micro-CT and computed tomography dimensional measurements

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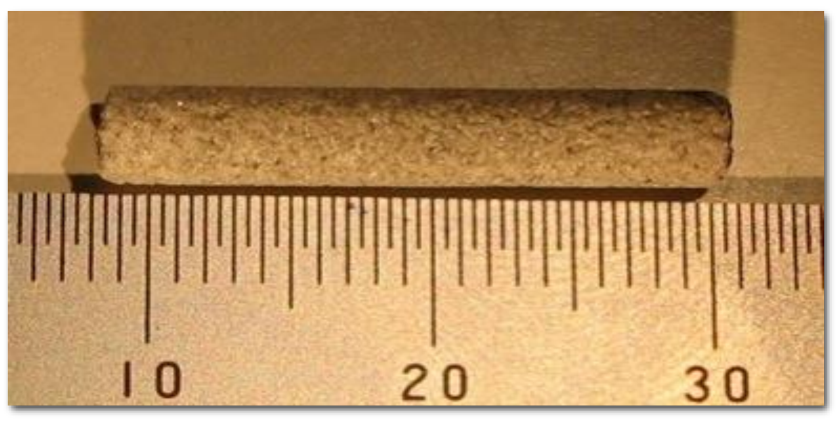
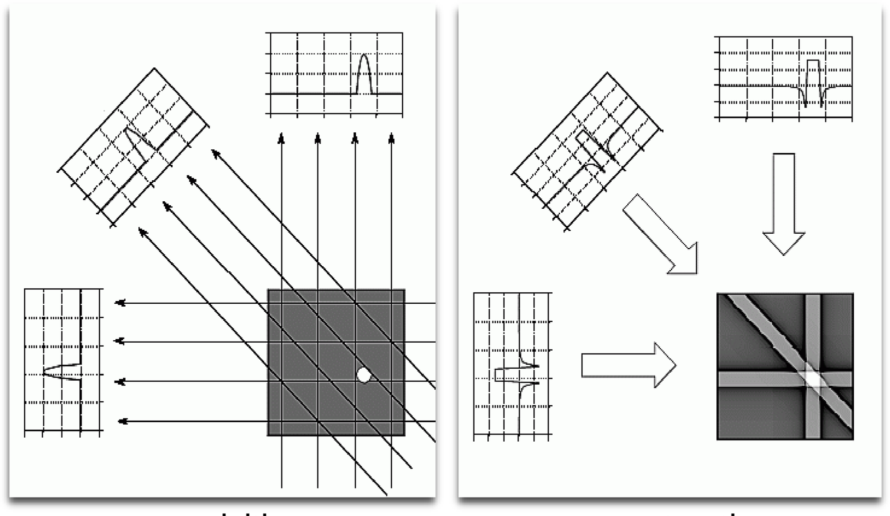
ABSTRACT

We demonstrate how for helical micro-CT, the ability to perform dimensional measurements on an image is intimately linked to image sharpness. This leads to a systematic way to make statements about uncertainty in the absolute scale of a tomogram. We use this to computationally reduce the measurement error, and therefore ensure system accuracy in terms of sphere-distance measurements, as defined in VDI 2630.



INTRODUCTION

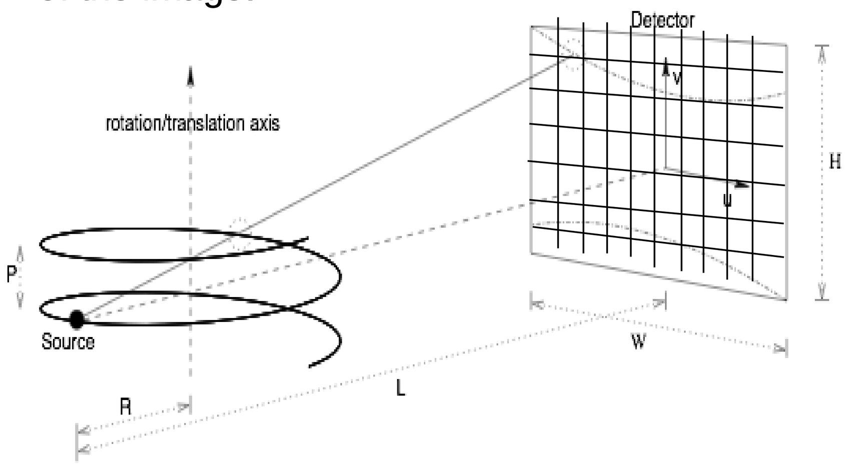
In order to use tomographic data in quantitative analysis, an absolute scale of the images is frequently needed. Unless we know the correct voxel size, we cannot expect to make meaningful statements about distances and dimensions. Equally important is the ability to make meaningful statements about measurement uncertainty. This is clearly important when verifying tolerances for manufactured parts, but it is equally important when studying physical properties of a sample by simulated experiments such as mechanical deformation or fluid flow.



Tomographic imaging is based on reconstructing a 3D representation of an object from a set of 2D projection images. In addition to the measured projection data, the reconstruction process requires knowledge about the acquisition geometry. Significant effort is needed in order to get the imaging hardware into a known geometric configuration before data acquisition -- aligning the system. Based on how accurately the system has been aligned for a given acquisition, this will impact on image quality, and on our ability to correctly determine the resulting voxel size.

Optimal units

Optimal units is a way to scale the geometric alignment problem such that misalignment by 1ou for any parameter corresponds to a ray through the sample is shifted by one pixel at the detector. Effectively, this causes a one-pixel blur of the image.

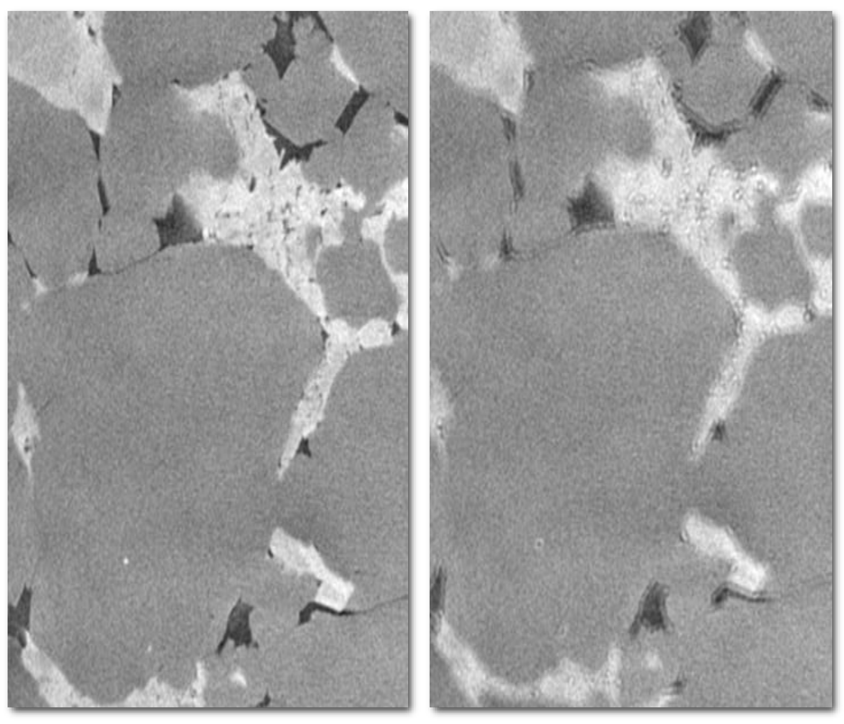


The sharpest image is obtained when all parameters are known to at better than 0.5ou accuracy.

MATERIALS AND METHODS

Autofocus

A method using image sharpness to computationally determine the acquisition geometry for a each dataset has previously been presented [1,2]. By inferring the acquisition geometry from the projection data, the micro-CT system no longer relies on accurate alignment to get good images. Rather, the acquisition geometry is reconstructed together with the tomogram.



Autofocus → Self callibration

For Helical trajectory:

- Autofocus determines geometric parameters better than 0.5ou.
- Distance from source to detector, and distance from source to rotation axis are both determined to within 0.5ou.
- The magnification of the system is accurate to about 0.5ou

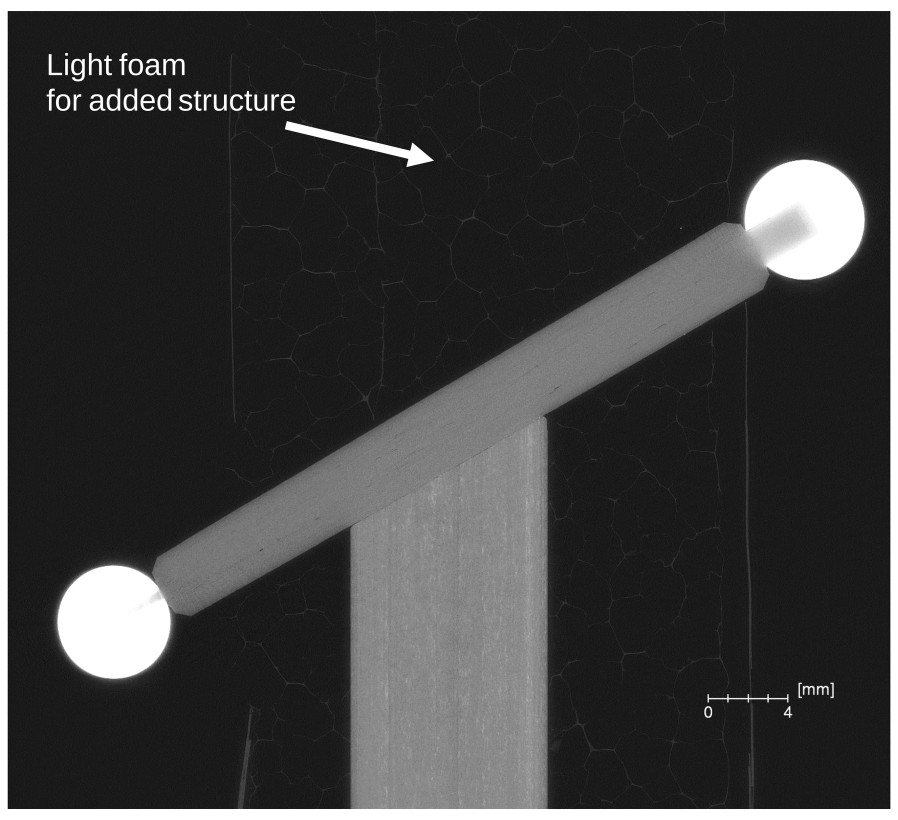
For a tomogram with 2500 voxels across, this implilies an accuracy of 1:5000, i.e., a relative error of about 2e-4.

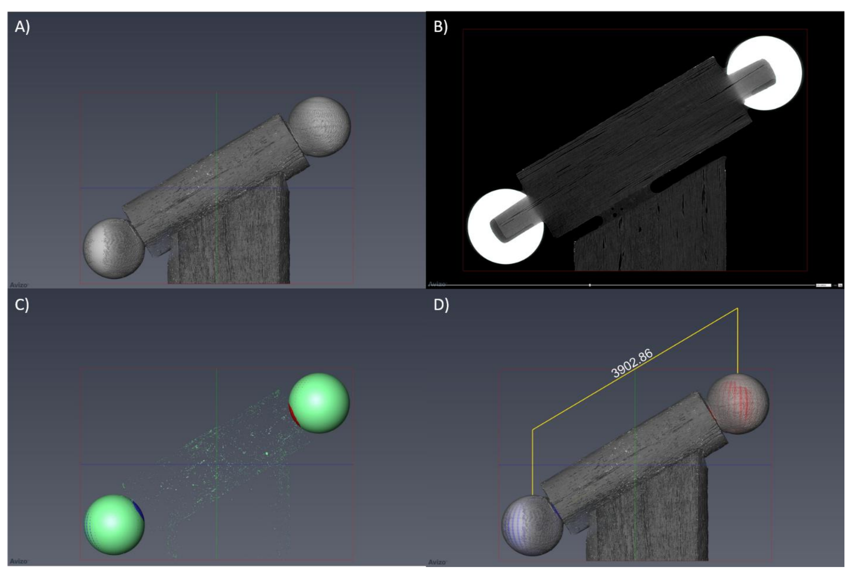
NO assumptions are made about hardware alignment accuracy, and is therefore independent of scale

Sphere distance measurements:

To quantify voxel-size accuracy, we use sphere distance measurements. Sphere distance is ideal for this purpose, because it can be determined from center-of-mass of each of the spheres. It is therefore largely independent of the choice of segmentation method, and properly characterizes the system rather than the segmentation algorithm.

We imaged certified phantoms consisting of ruby balls separated by known distances; ~4mm, ~16mm and ~40mm. By comparing sphere distances obtained from the tomograms to the physical sphere distance as specified by the manufacturer with 1µm accuracy. The phantom was wrapped in a light foam to ensure structure all the way to the edge of the tomogram.





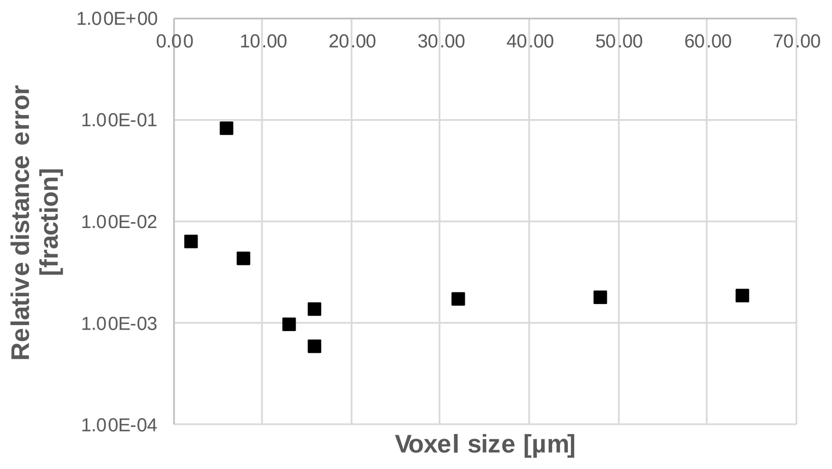
A) 3D rendering of the ruby balls phantom, B) typical vertical 2D ortho-slice images, C) 3D visualization the extracted surface model (green) and fitted sphere geometries (red and blue) and D) results of the spheres centres distance measurements.

Distance measurements of the tested phantoms were performed with Avizo™ for Industrial Inspection version 9.7, using Avizo XMetrology Extension:

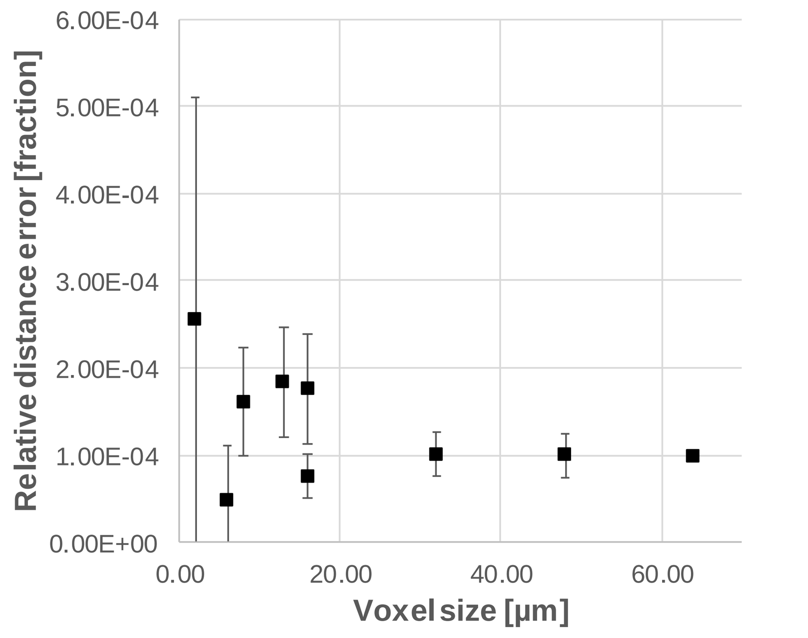
1. 3D tomogram data was used without any pre-processing
2. Adaptive Sub-Voxel algorithm was applied for metrology surface determination. The surface was generated based on morphological Laplacian filter and Auto Thresholding mode, providing results with a precision smaller than the actual voxel size of the acquired data
3. A sphere geometry was fitted to each of the ruby balls using 10 points lying on the determined surface
4. The distance between centres of the fitted spheres was measured.

RESULTS

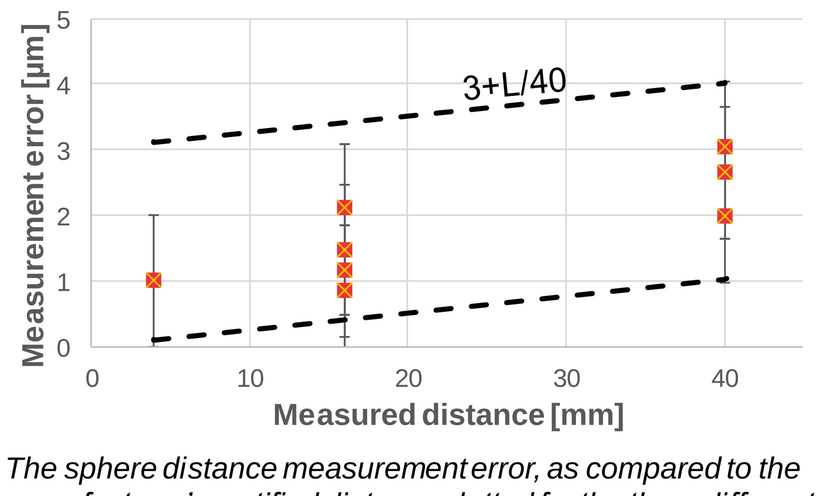
We first compute sphere distances using the voxel size reported at acquisition time, *i.e.*, based on hardware alignment. It is clear that the system is only partially aligned, and suited for imaging with voxel sizes above 10µm only. With autofocus-obtained voxel size, we reliably get relative error less than 2e-4, all the way down to imaging with 2µm voxel size.



Relative distance error using voxel size determined from hardware alignment.

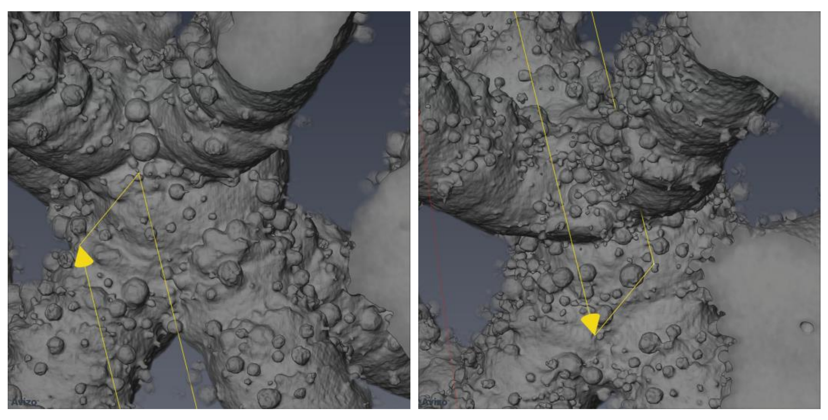


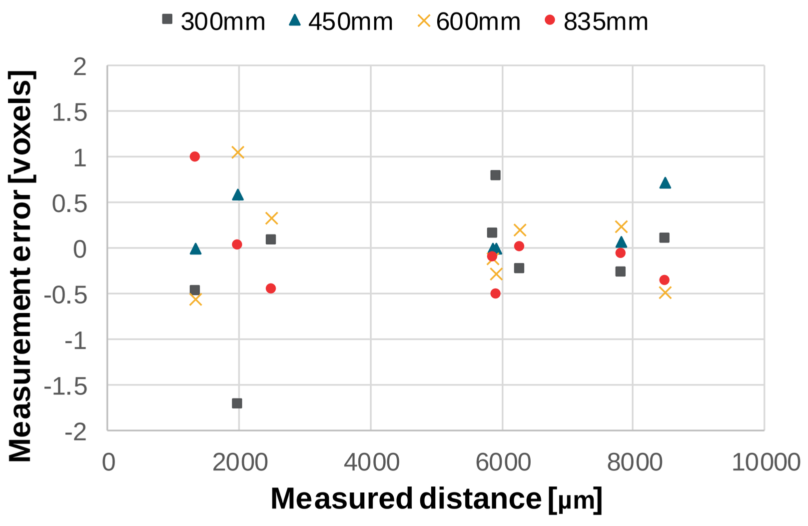
Relative sphere distance measurement error as a function of tomogram voxel size. The error bars indicate manufacturing tolerance for the phantom used.



The sphere distance measurement error, as compared to the manufacturer's certified distance plotted for the three different phantoms. For reference, the dashed lines (0 + L/40), and (3+L/40). The error bars indicate manufacturing tolerance for the phantoms.

Finally, we demonstrate robustness of the self-calibration system by comparing outcomes from imaging a 3D printed titanium scaffold. Voxel size was in this case about 2.8µm. The same sample was imaged four times with different acquisition geometry. Eight lengths were picked out by hand, and measured in each tomogram For each length we consider deviation from mean value.





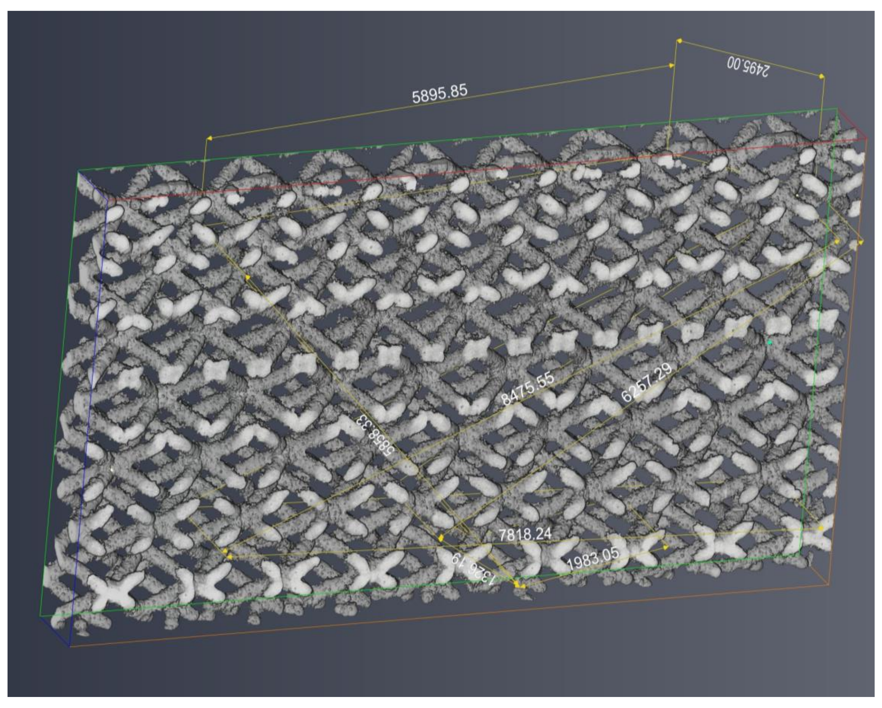
The deviation is on the order of 1 voxel, regardless of measurement length, with no obvious pattern for each tomogram (labeled according to source-detector distance used). This suggests that the deviation is dominated by uncertainty in how the end-points were picked out, rather than from error in tomogram.

Repeatability of measurements does in this case not depend on the tomogram, but on the measurement procedure.

CONCLUSIONS

Optimal units lead to a natural way to consider voxel-size uncertainty. For a particular acquisition geometry, we can *a priori* make statements about achievable voxel-size accuracy being better than half a voxel over the width of the tomogram, irrespectively of hardware alignment accuracy, and irrespectively of voxel size.

It is clear that this is predecated on sufficient structure in the tomogram. In particuarl, it is clear that structures towards the edge of the tomogram, where the reconstruction is most sensitive to misalignment, is important to achieve this accuracy.



REFERENCES

[1] A Kingston, A. Sakellariou, T. Varslot, G. Myers, A. Sheppard. *Reliable automatic alignment of tomographic projection data by passive auto-focus.* Medical Physics, vol 38(4934). 2011.
[2] T. Varslot, A. Kingston, G. Myers, A. Sheppard. *High-resolution helical cone-beam micro-CT with theoretically-exact reconstruction from experimental data.* Medical Physics, vol 38(10). 2011.