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Characterising the Positioning System of a Dimensional Computed Tomograph (CT)

Benjamin A. Bircher*, Felix Meli, Alain Küng, Rudolf Thalmann

Federal Insitute of Metrology METAS, Laboratory for Length, Nano- and Microtechnology
Lindenweg 50, 3003 Bern-Wabern, Switzerland

* *Corresponding author: benjamin.bircher@metas.ch*

Abstract

Computed tomography (CT) is increasingly used for dimensional characterisation of workpieces. Therefore, the Federal Institute of Metrology METAS is developing and building a unique metrology CT system to measure workpieces of millimetre dimensions with sub-micrometre resolution, and to study CT metrology and traceability in general. Here, an overview of the CT system is presented and the requirements related to the positioning system and its characterisation are discussed in detail. The results indicate that further *in situ* measurement systems are required to correct high-resolution CT scans for geometrical errors.

1 Introduction

1.1 Dimensional computed tomography (CT)

While medical computed tomography is now used for nearly five decades, the method was only recently applied for dimensional metrology. During a CT scan, X-ray projections of an object under investigation are recorded from different viewing angles and reconstructed into a three-dimensional model using mathematical transformations [1]. The unique feature of CT, to measure entire object geometries, renders the method suitable for investigation of internal geometries and features too small for tactile probing. Recent developments in the performance of CT components, such as X-ray tubes and detectors, as well as new manufacturing processes, e.g. additive manufacturing, are moving the field forward [2]. However, the measurement uncertainty remains rather high compared to tactile measurements [3], the estimation of the uncertainty proves to be challenging [1] and standardisation is still ongoing [4].

The accuracy of CT scans is influenced by a considerable number of factors, including effects originating from the X-ray generation, interaction with the object, and detection; CT geometry errors; and the reconstruction and analysis algorithms [1]. When aiming at sub-micrometre accuracy, the geometry of the CT system, i.e. the position of the X-ray source spot with respect to the workpiece and the detector, can be a major source of error. Thereby, the absolute positions as well as the long-term stability of the components are critical. Typically, some of the geometric parameters are determined prior to a measurement using calibrated reference objects. To supersede such lengthy calibration steps, we intend to characterise our home-built CT system, METAS-CT, to a sufficient extent and equip it with additional measurement systems. An important part of such characterisation includes measuring the guideway errors of the employed axes, i.e. the motion of the axes along the five degrees of freedom that are theoretically constrained [5].

In this paper, the ideal CT geometry is discussed prior to introducing the design considerations of the METAS-CT system. The guideway error characterisations of all axes of the CT system are presented and discussed.

1.2 Ideal cone-beam CT geometry

A cone-beam CT consists of an X-ray point source, a rotary axis with an object attached, and a planar detector (see figure 1). The connecting line between the X-ray source and the centre of the detector is referred to as magnification axis. An ideal cone-beam CT fulfils the following conditions [6]: The magnification axis is (i) orthogonal to the detector plane and (ii) intersects the centre of the detector; the rotary axis is (iii) parallel to the detector pixel columns and (iv) orthogonally intersects the magnification axis. Uncorrected deviations cause artefacts in the CT data [7], because the reconstruction algorithms usually assume an ideal geometry. To avoid this, the geometry has to be either very close to the ideal case or the data needs to be corrected before or during reconstruction. Furthermore, the source-object (SOD) and source-detector distances (SDD), which determine the magnification (SDD/SOD), must be accurately known to avoid scaling errors.

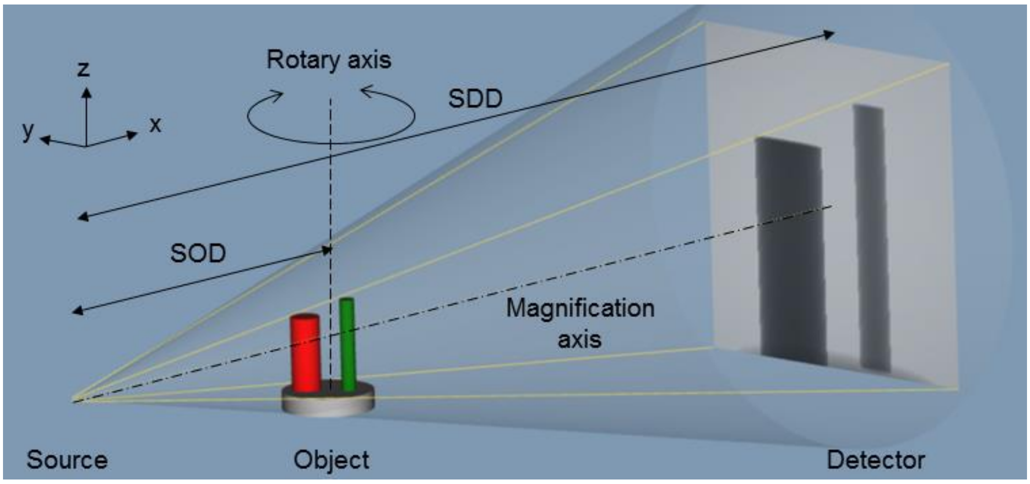

Figure 1: An ideal cone-beam CT system consisting of an X-ray source, an object attached to a rotary axis and a detector. The source-object (SOD) and source-detector (SDD) distances must be known.

2 METAS-CT design considerations

METAS-CT is designed to investigate small objects with sub-micrometre resolution. Figure 2 shows the system at its current stage of development. A sub-microfocus X-ray tube (XWT-190-TCNF, X-RAY WorX) with a maximal energy and target power of 190 kV and 50 W is used. This enables maximal penetration lengths (at 1:10 contrast) of approximately 10 mm for heavy metals (e.g. steel), 50 mm for light metals (e.g. aluminium, titanium, glass), and 140 mm for plastics. To capture X-ray projections, a digital flat panel detector (XRD 1611 CP3, Perkin Elmer) with a CsI:Tl scintillator, 4000 x 4000 pixels, a pixel pitch of 100 µm and 16-bit intensity resolution is used. Thus, the maximally achievable voxel resolution is 1 µm for 4 mm and 10 µm for 40 mm objects. At such high resolutions the size of the X-ray source spot becomes a limiting factor [8]. To achieve such small source spots, the target power has to be reduced, entailing low X-ray intensities. Consequently, increased exposure times and, thus, long scan times of several hours have to be taken into account. Therefore, the long-term stability of the system is of major importance.

For this reason, a METAS positioning system concept, based on air-bearing rotary and linear axes, was manufactured by LAB Motion Systems. The rotary stage, carrying the object under investigation, forms the core of the system (see figure 2, Rot). To improve the stability, a minimal number of additional linear axes is used: X1 and X2 are vacuum preloaded air-bearing axes with a linear drive using the same guideway and, thus, enabling a co-linear displacement of the rotary stage and the detector by 1000 mm each. This enables source-object distances (SOD) of approximately 0 mm to 1000 mm and source-detector distances (SDD) of 400 mm to 1400 mm. Thus, the magnification as well as the cone-beam angle can be adjusted. The Z-stage features a magnetically preloaded air-bearing with a ball screw spindle drive. The vertical displacement range of the rotary stage is 300 mm. Thus, the object on the rotary stage can be retracted from the X-ray beam, to record flat field images for detector calibration. Furthermore, helical scan trajectories can be realised that enable more accurate measurements [9].

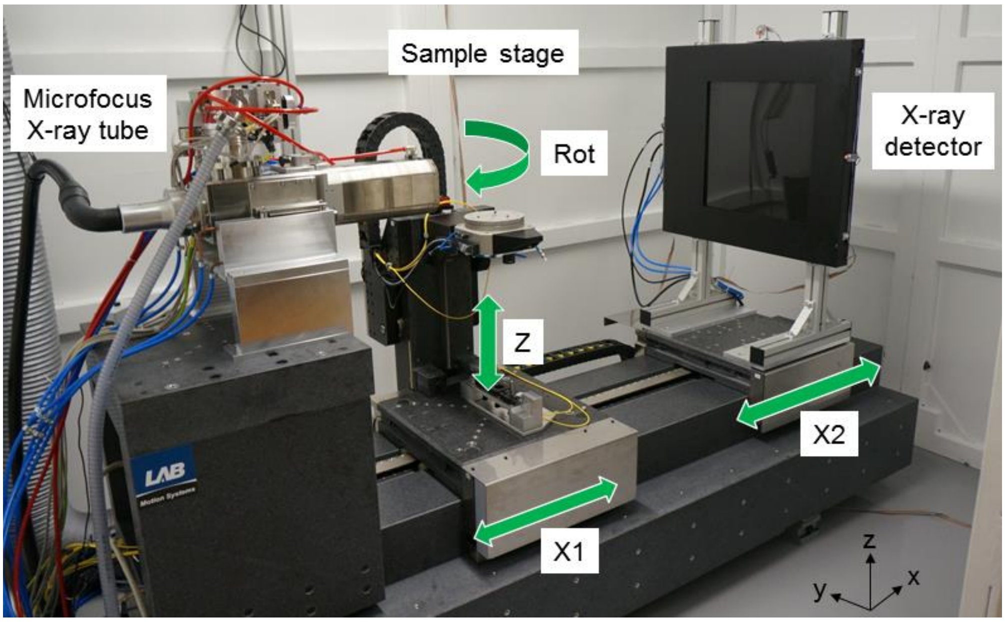

Figure 2: Overview of the METAS-CT system consisting of a 190 kV microfocus X-ray tube, a flat panel X-ray detector, and an air bearing positioning system. The sample can be rotated (Rot-stage) and displaced vertically (Z-stage). The sample and the detector can be moved co-linearly along the magnification axis using stages X1 and X2, respectively.

3 CT positioning system characterisation

A crucial step in characterising the CT geometry is measuring the guideway errors, since they result in deviations from the ideal geometry shown in figure 1. All subsequent measurements of the rotary and the linear axes were performed at (20 ± 0.5) °C.

3.1 Rotary axis

The rotary stage is a key component of an industrial CT system, since it is used to mechanically realise the sample rotation. A certain number of X-ray projections, i.e. angular increments, have to be recorded to sufficiently sample the volume. According to reference [10], the required number of projections is $\pi/2$ times the object diameter in pixels. However, for certain measurements a lower number of projections can be sufficient [11]. When using 95 % of the width of the employed 4000 x 4000 pixel detector, maximally 6000 projections are required, resulting in angular increments of 1 mrad. The positioning accuracy should thus be at least 0.1 mrad. The rotary stage runout errors directly influence the accuracy of CT measurements; they should be of the order of 1/10 of the voxel size, i.e. 0.1 µm at the highest magnification.

The METAS-CT system employs an air-bearing rotary stage with a direct drive motor (RT150S, LAB Motion Systems). The axial and radial error motions, as well as the positioning accuracy were characterised. It is emphasised, that the radial error motion needs to be measured in two spatial directions; in contrast to a roundness measurement device, where it is sufficient to characterise the radial error motion in direction of the tactile probe [12]. The rotary stage was measured in the final mounting and load condition using capacitive probes (Lion Precision) against a spherical reference object (Ø ½“, tungsten carbide, form deviation 0.025 µm at 50 UPR) for the axial and radial error motion. The sensitivity of the capacitive probes on the spherical counter-surface was determined to be

2.2 µm/V by comparing to an interferometer. The rotary stage was rotated at 5 RPM and averaged sets of 200 data points from the capacitive probes were sampled at 33 Hz. For the radial error measurements, the form error of the spherical reference object was partially separated by orienting it at 0° and 90° and averaging the two measurements. A fitted sine was subtracted from the data to account for the eccentricity of the reference object position and the data was filtered with 50 UPR. For the axial error measurements, the sphere was centred within 0.4 µm using one capacitive probe, whereas the other probe was positioned in the polar region. To exclude that the observed 16 undulations originate from the spherical reference object, a second measurement was performed for error separation with the sphere rotated 11.25°, which corresponds to half an undulation. The resulting data was offset corrected, averaged and filtered with 50 UPR. The positioning accuracy of the rotary stage was determined using an autocollimator (ELCOMAT 3000, Möller-Wedel) and a calibrated 36-sided optical polygon (ZG Optique SA).

Figure 3 shows the results of the rotary stage guideway error measurements. The axial error motion (figure 3a) was 0.05 μm_{pp}, which is within the above stated requirements. The radial errors at 57 mm and 100 mm above the rotary stage surface were, respectively, 0.10 μm_{pp} and 0.20 μm_{pp} in y-direction and 0.06 μm_{pp} and 0.11 μm_{pp} in x-direction (figure 3b). This is partially greater than the required accuracy of 0.1 µm, however, since the repeatability of the errors was within 0.05 μm_{pp}, these errors can be accounted for during an image post-processing step using a look-up table. Finally, the measured angular positioning accuracy was corrected for radial runout of the encoder by subtracting a sine function (figure 3c). Subsequently, it was below 0.04 $mrad_{pp}$, which is well within the required range of 0.1 mrad.

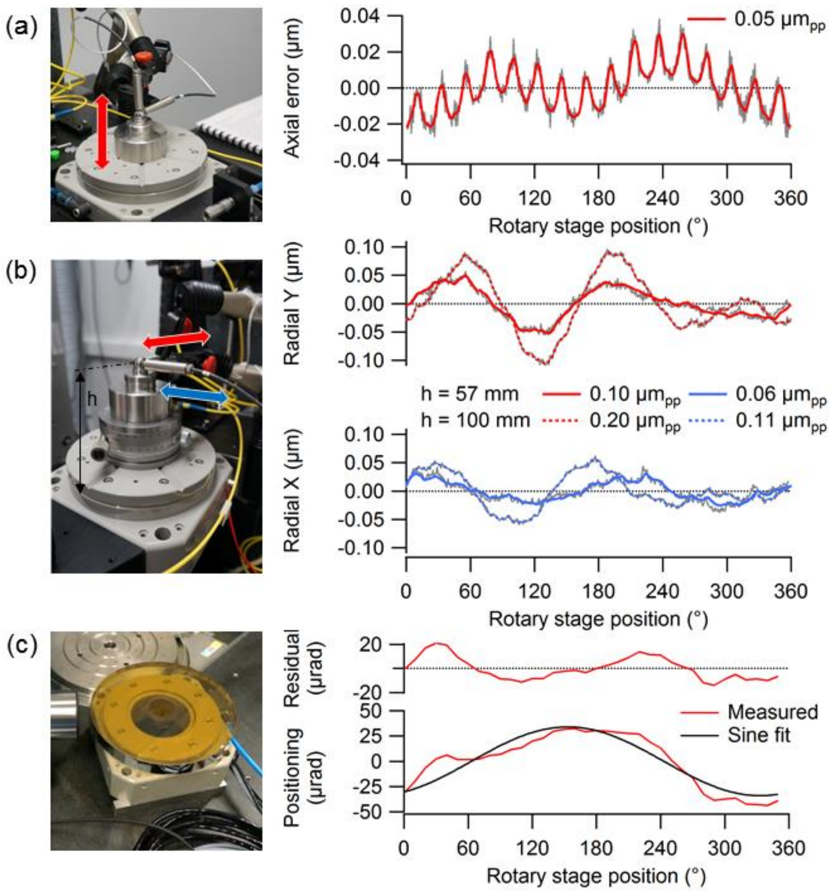

Figure 3: Rotary stage characterisation: (a) Axial error motion and (b) radial error motion measured using capacitive probes. The coloured lines represent data filtered with 50 UPR and the grey lines the unfiltered average data. The radial error was determined in direction x (blue) and y (red) and at two heights, h = 57 mm and h = 100 mm, above the rotary stage surface. (c) Measurement of the positioning accuracy using an autocollimator and an optical polygon.

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3.2 Linear axes

Formulating the demands on the guideway errors of the linear axes is not as straightforward as for the rotary stage. Strictly speaking, the translational error motions perpendicular to the magnification axis should be 1/10 of a voxel, i.e. 0.1 µm at the highest magnification. The maximally permissible angular errors depend on the object dimensions as well as the object placement above the rotary stage. Considering an extreme case, such as a helical scan trajectory with a Z-stage displacement over 100 mm, they should remain within 1 µrad. Except for helical scans, the linear axes are stationary during a CT scan, thus, it is easier to correct their guideway errors in the data. Errors such as a detector displacement perpendicular to the magnification axis (y-direction) can easily and accurately be determined from the X-ray projection data. Angular and magnification errors usually have to be determined by scanning reference objects.

To characterise the straightness and angular error motion of the linear stages, the following measurement principles were employed (figures 4a and 5): Straightness deviations were measured using a dial test indicator (lever type) against a calibrated ceramic straight edge (Mitutoyo, length 700 mm, straightness deviation 0.74 µm). For axes X1 and X2 the straight edge was measured in two positions to cover the full stroke of 1000 mm. The pitch and roll errors of X1 and X2, and pitch and yaw errors of Z, were characterised using electronic levels (Leveltronic A40, WYLER). The yaw errors of X1 and X2 were measured using two interferometers differentially (FPS3010, attocube). The coordinate system indicated in figures 4a and 5 was used for all measurements and the values are referred to the central axis of the linear guideway, except for the Z-stage where the centre of the rotary stage was used as reference. The straightness measurements were corrected for the Abbe offset using the measured angular errors, the form error of the straight edge using its calibrated value, and parallel misalignment by subtracting a linear function.

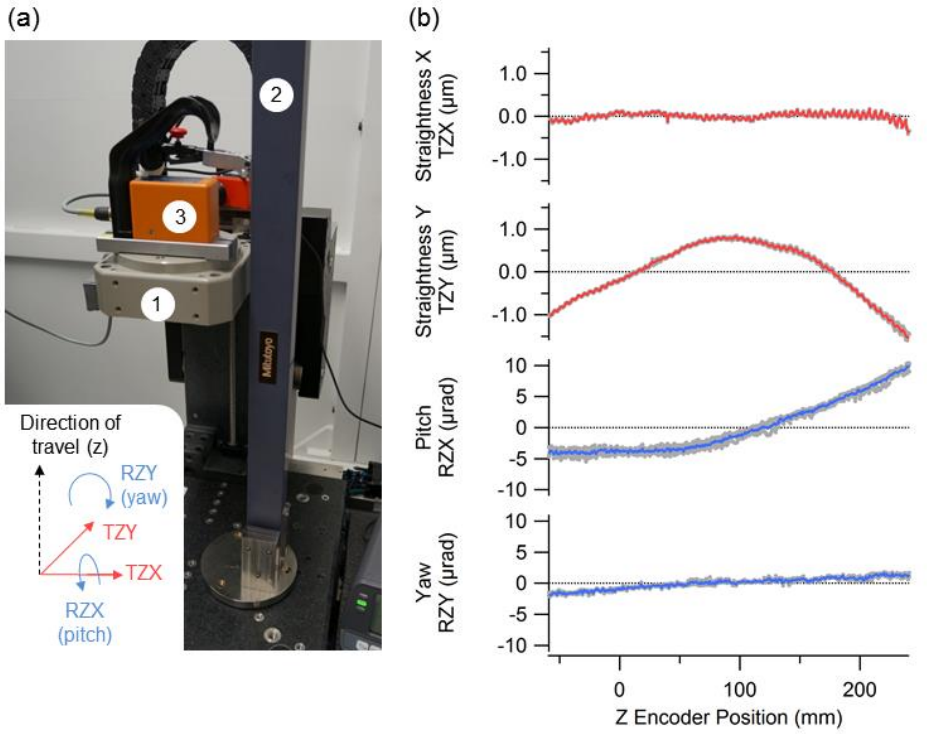

Figure 4: (a) Measurement setup to determine the straightness (TZX) and the yaw error (RZY) of the Z-stage relative to the centre of the rotary stage (1) with a straight edge (2) and an electronic level (3). The coordinate system is indicated in the bottom left corner. (b) Measured guideway errors of the Z-stage. Shown are horizontal straightness X and Y in red and the pitch and yaw errors in blue. The solid lines indicate the average value of all measurements (grey markers).

Figure 4a shows the setup for measuring the straightness (TZX) and the yaw error (RZY) of the Z-stage. The measured error motions of the Z-stage are shown in figure 4b. Whereas TZX (0.5 μm_{pp}) and RZY (3.5 μrad_{pp}) are confined by two counteracting air-bearings, TZY (2.4 μm_{pp}) and RZX (14.2 μrad_{pp}) are confined by magnetically preloaded air-bearings. This might explain the considerably higher error motions, because the flatness and alignment of the magnetic guideway may have a critical influence on the results. The small undulations in the straightness data match the pitch (5 mm) of the spindle-drive and are likely caused by spindle runout. In addition to the guideway errors, the cantilever shaped Z-stage is subject to a load dependant static pitch (RZX) error that was determined to be of the order of 1 µrad/N (force applied in the centre of the rotary stage).

The setup for the characterisation of the X1- and X2-stage is shown in figure 5 and the corresponding results in figure 6. The measured horizontal and vertical straightness deviations, respectively, were within 0.5 μm_{pp} (TXY) and 1.6 μm_{pp} (TXZ). Since the two carriages utilise the same bearing surface, the error motions coincide inside the overlap region (encoder position -235 mm to 300 mm). All measured angular errors were within 6 μrad_{pp} for X1 and X2. The increased noise floor for the roll and pitch motion is due to the used electronic levels, whereas the yaw was measured using two interferometers differentially. In summary, these results indicate high-precision linear bearings, however, they are an accuracy limiting factor for high-resolution CT scans.

4 Conclusion and Outlook

We have presented the design of METAS-CT, a dimensional CT system for the characterisation of small workpieces. It consists of a high-resolution X-ray tube and detector, thus, posing increased demands on the positioning system. For this reason, the positioning system was carefully characterised. The error motions of the rotary stage, a key component of the CT system, are sufficiently small for most scans. However, they should be considered in scans with voxel sizes of the order of 1 µm. Since their repeatability was within the requirements, this can be done using a look-up table. The error motions of the linear axes are small (within 3 μm_{pp} and 15 μrad_{pp}), but could still impair high-resolution CT scans. The guideway errors lead to a total positioning error of the order of 5 µm and angular errors up to 20 µrad on the rotary stage surface. Whereas repeatable errors can be corrected using look-up tables, the long-term stability of the CT system suffers from the large machine dimensions and a considerable heat load, originating from the X-ray tube (~80 W) and the detector (~90 W), during normal operation. This leads to temperature offsets and gradients with respect to the calibration condition, which can cause drifts that are increased by long scan times of several hours. Furthermore, the rotary stage is subject to load dependant angular errors that vary with the weight of the investigated object. Ultimately, the reconstruction algorithm requires an absolute CT geometry including the absolute source-object and source-detector distances, as well as all tilt errors between the rotary axis and the detector plane.

Therefore, we conclude that additional sensors are required to monitor the geometry of the CT system. Such an *in situ* metrology system is currently developed and will be fitted into METAS-CT. This enables an accurate correction of the geometrical errors, either by post-processing of the projection images or by using a reconstruction algorithm that accepts the parametrised geometry of each projection image. Additionally, the CT system is equipped with a multi-channel temperature measurement system and water cooling systems to reduce the head load. The *in situ* metrology system in combination with the temperature measurement system will be used for studying the response of the CT geometry to thermal loads and the resulting temperature gradients.

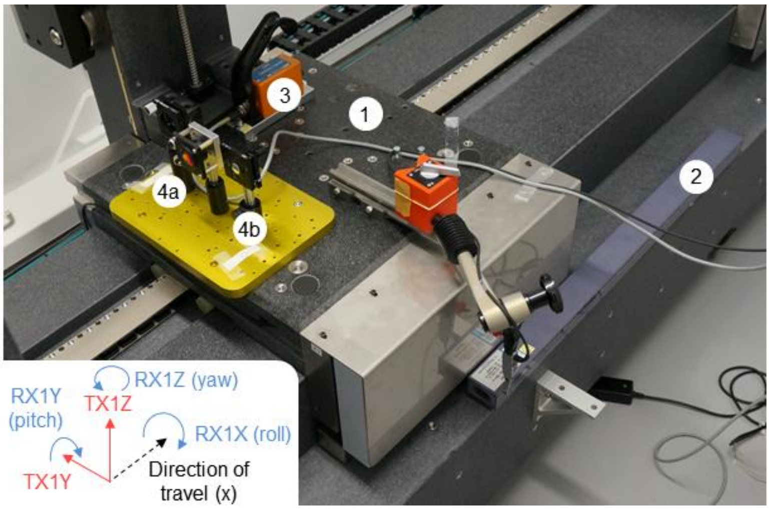

Figure 5: Measurement setup to determine the straightness (TX1Y), the pitch error (RX1Y) and the yaw error (RX1Z) of the X1-stage (1) using a straight edge (2), an electronic level (3), and a differential interferometer (visible are two mirrors 4a and 4b). The coordinate system is indicated in the bottom left corner; the X2-stage was measured accordingly.

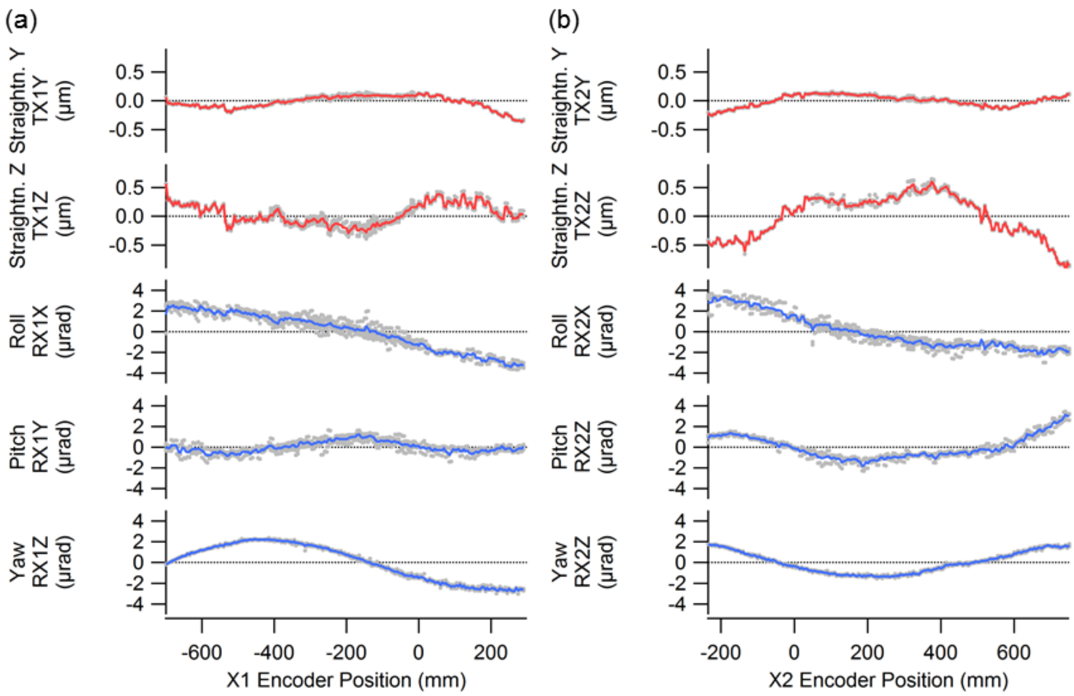

Figure 6: Measured guideway errors of the X1 (a) and X2 (b) linear stages. Straightness Y (horizontal) and Z (vertical) are shown in red and the roll, pitch and yaw errors in blue. The solid lines indicate the average value of all measurements (grey markers).

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