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Sensitivity analysis of the geometrical misalignments of X-ray computed tomography systems on dimensional measurements

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Abstract

X-ray computed tomography (XCT) is increasingly used in dimensional metrology. However, the accuracy enhancement of XCT-based measurements still represents a major challenge due to the large number of influence factors. This work focuses on the enhancements that are achievable by monitoring and correcting the system geometry, through the inspection of parameters describing the relative position and orientation between the hardware components. The work is part of a research project aiming at (i) achieving a complete understanding of the geometry-dependent effects on XCT measurement results and (ii) developing a fast and easy-to-implement procedure per the system geometry characterization and correction. At the scope, a simulation-based sensitivity analysis was designed to investigate the relationship between the deviation of geometrical parameters from the optimal/aligned configuration and the accuracy of dimensional measurements, with the aim of identifying the most critical parameters to be examined and corrected. The effect of each type of geometrical misalignment was tested separately. The study was carried out using a dedicated reference geometry, specifically designed for the purpose.

X-ray computed tomography, dimensional metrology, geometrical misalignments, sensitivity analysis

1. Introduction

X-ray computed tomography (XCT) is an advanced non-destructive measuring technique, which is increasingly used in manufacturing metrology [1]. However, the traceability establishment of CT dimensional measurements is still a challenging task because of a large number of influence factors, including the system geometry [2]. The most used configuration in industrial XCT systems is characterized by three main hardware components: (i) X-ray source emitting an X-ray cone beam, (ii) motion system equipped with a rotary stage and (iii) X-ray detector. In order to avoid artefacts in the reconstructed volume and to enhance the accuracy of XCT dimensional measurements, strict alignment conditions between these components must be respected [3]. It is therefore necessary to achieve a clear and complete understanding of the geometry-dependent effects on XCT measurement results in order to develop fast and easy-to-implement procedures to characterize and correct the system geometry.

2. Materials and methods

A simulation routine was developed with the scope of investigating the relationship between the deviation of geometrical parameters from the aligned configuration and the accuracy of dimensional measurements, to identify the most critical parameters. A ball plate composed of 56 ruby spheres of 1 mm diameter arranged on a carbon-fiber-reinforced polymeric plate was designed for the research project of which the present work is part [4]. In this work, 49 spheres placed in a regular 7×7 grid and equally spaced by 5 mm were considered to investigate the effects of measuring direction, location and different test lengths in a single scan. The object was placed in the simulated CT system coordinate frame as seen in Figure 1, so that the central row and central column of spheres are projected respectively onto the central pixel row and column of the detector. In this way, the 2D area of the detector is covered homogeneously and can be investigated efficiently. XCT scans were at first simulated with the system ideally aligned, taking the measured spheres centre-to-centre (C2C) distances and form errors as reference. Subsequent simulations were done to investigate each type of geometrical misalignment, starting from the misalignment magnitudes already tested in literature [5] and then adding smaller misalignments to precisely identify the critical values.

The simulations were performed using the software tool aRTist 2.0 (BAM, Germany). The 3D reconstruction was performed assuming the system aligned in all simulated cases, via the filtered backprojection algorithm implemented in the software CTPro 3D (Nikon Metrology, UK). The analysis and visualization software VGStudio MAX 3.2.3 (Volume Graphics GmbH, Germany) was used to determine the spheres surface by a local-adaptive algorithm, and to perform the measurements of interest (i.e. C2C distances and form errors).

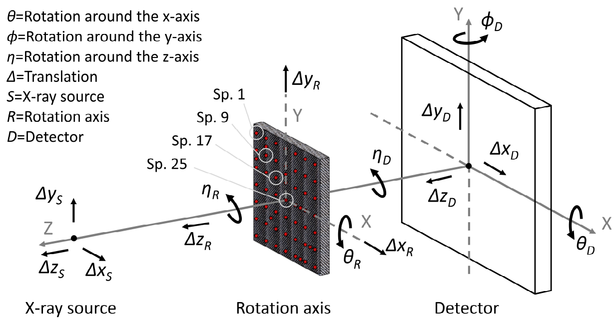

Figure 1. Schematic representation of the CT ball plate positioned in the system coordinate frame. The misalignments considered in the study are indicated with positive sign.

3. Results

Out-of-plane rotations of the detector (θ_D, ϕ_D) and of the rotary stage axis (θ_R) were found to cause significant C2C measurement errors, even for small angle amplitudes (see Figure 2). In particular, the errors due to θ_D and θ_R show similar trends, which vary depending on the measured distance and angular misalignment. Moreover, such misalignments induce a localized scale error that was determined to be dependent on the measuring direction. The slant of the detector, ϕ_D, caused C2C measurement errors along the X direction and the diagonals, which increase with the measured length. Less relevant errors were instead found along the Y direction.

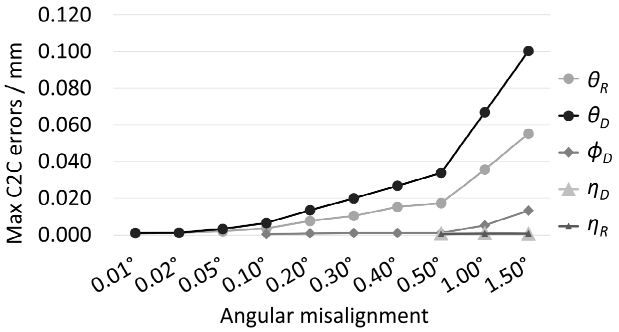

Figure 2. C2C measurement errors obtained with varying angular misalignments of detector and rotary stage axis.

The positional shifts of detector, rotary stage and source along the z-axis (Δz_D, Δz_R and Δz_S) cause C2C measurement errors that depend on the misalignment magnitude and increase with the measured distance. Δz_D resulted to be less critical with respect to Δz_R and Δz_S, as illustrated in the example in Figure 3.

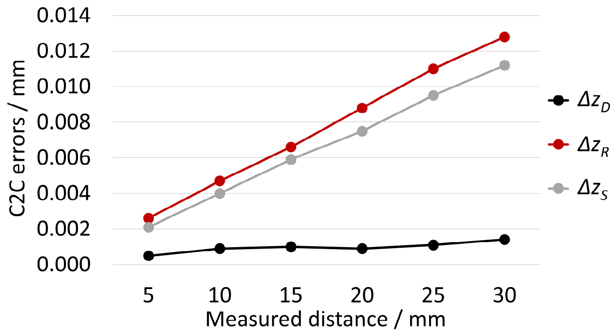

Figure 3. Example of C2C measurement errors calculated with a positional shift Δz = 0.05 mm of detector, X-ray source and rotation axis for varying measured distances.

Among the investigated misalignments, the slant of the detector (ϕ_D) and the tilt of the rotary stage axis (θ_R) were found to significantly influence the evaluation of the spheres form error. ϕ_D causes significant deviations of the measured spheres form for angles greater than 0.5° with respect to the reference values (see Figure 4). In this case, the spheres are erroneously reconstructed with a torus-like shape. Such deformation is more critical along the X direction than along the Y direction. The deformation induced by θ_R depends on the sphere position and on the angle amplitude, as illustrated in Figure 4. Deviations with respect to the reference form errors start to be significant from θ_R = 0.1° and for the spheres placed at the four corners of the ball plate.

The shifts along the X- and the Y-direction (Δx and Δy) of all the XCT system components, as well as in-plane rotations of the detector (η_D) and rotary stage axis (η_R), resulted less critical, as no significant measurement errors were observed.

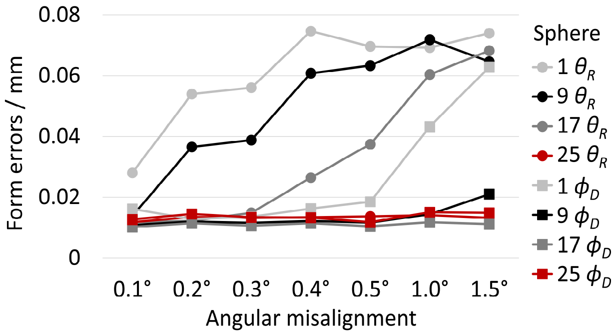

Figure 4. Sphere form error evaluated on the spheres that lie into the diagonal (i.e. no. 1, 9, 17 and 25), varying the tilt of the rotary stage axis (dots) and the slant of the detector (squares).

4. Discussion and conclusions

This work presented the main results of a simulation-based sensitivity analysis of the effects of geometrical misalignments on XCT-based dimensional measurements, designed to identify the most critical parameters and develop a fast and easy-to-implement method to assess and correct the system geometry.
Simulations were focused on the measurement of spheres C2C distances and form errors of a ball plate in both cases of perfectly aligned XCT system and system where different types of geometrical misalignments were individually and purposely induced. The tilt of the detector and of the rotary stage axis, the slant of the detector and the shift along the Z-axis (i.e. magnification axis) of all the XCT hardware components resulted to cause significant C2C measurement errors, even for small misalignment values. In addition, the tilt of the detector and of the rotary stage axis were found to have a great impact on the evaluated spheres form. The effects of measuring direction, sphere location and tested length on the measurement results were also shown in this work.
The study allowed achieving a complete simulation-based model of the effect of each geometrical misalignment on the accuracy of dimensional measurements and identifying the next steps for the research. The ongoing experimental validation of the simulation results is focused on the parameters determined to be critical in this study. Future work is also planned to investigate the effect of combined misalignments as well as the impact of the magnification and of other factors (e.g. finite dimension of the focal spot, detector pixel size and scan noise).

Acknowledgments

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