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Geometry of X-ray computed tomography systems: a sensitivity analysis of detector angular misalignments on dimensional measurements

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Abstract
X-ray computed tomography (XCT) is increasingly used in industrial metrology for dimensional measurements of products and components characterized by complex structures, internal features or non-accessible surfaces. However, the accuracy of XCT-based dimensional measurements is affected by several influence factors. One critical factor is the system geometry, i.e. the relative position between the hardware components and their alignment. A number of methods for system calibration based on the characterization of all geometrical parameters have already been proposed in literature, but they are typically time consuming and can be difficult to be implemented by final users. This work is part of a study that aims at evaluating the dimensional measurement errors due to different geometry misalignment conditions, in order to (i) understand the effective necessity to inspect all the parameters and (ii) develop a faster and easier method to control and correct the geometry of a XCT system. The work focuses on a simulation-based sensitivity analysis of detector angular misalignments on XCT dimensional measurements. Each geometrical parameter is studied individually to quantify its effect.

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

1. Introduction

X-ray computed tomography (XCT) is increasingly used for non-destructive inspections and metrological verifications of industrial components characterized by complex and/or freeform structures, internal surfaces and micro-scale features [1]. However, the traceability establishment of XCT-based dimensional measurements is still a challenge because of a multitude of influence factors, including system geometry. Most industrial XCT systems commonly used for dimensional metrology applications are characterized by a cone beam configuration, which includes three main components: an X-ray source, a handling system equipped with a rotary stage and an X-ray detector. These components need to be placed according to precise alignment conditions to achieve accurate measurement results. Therefore, the precise knowledge of the XCT system geometry is of fundamental importance. In literature, different methods for the geometrical calibration of XCT systems have been presented [2,3]. In most cases, the proposed solutions are focused on the characterization of the entire geometrical conditions of the system [2], hence resulting to be time consuming and often difficult to implement by final users. These drawbacks are incompatible with the industrial requirements of speed and smart tools. Other works studied the effect of specific systems misalignments [3-7], and the present work aims at going on in this direction to obtain a clear comprehension of the impact of each type of misalignment on the accuracy of XCT dimensional measurements. This work is part of a bigger study that is focused on improving such understanding, which is needed to develop faster and easier-to-implement procedures. In particular, detector angular misalignments are the focus of this work.

2. Materials & methods

In the present work, a simulation campaign is performed to characterize the effect of every possible detector angular misalignment on XCT dimensional measurements, starting from observations proposed in literature. Ferrucci et al. [6] showed that a misalignment around Z-axis (skew; see Figure 1b for axes definition) is more critical with respect to the ones around X-axis (tilt) and Y-axis (slant), but just few angles were inspected and, in particular for tilt and slant, focusing on large angles (5° and 10°). The impact of detector misalignments around the X-axis were analysed also by Aloisi et al. [7], measuring the sphere-to-sphere distances of a calibrated ball bar. It was shown that (i) the measurements errors increase from 12 µm with 0.5° tilt to 28 µm with approximately 1.5° and (ii) the position of the ball bar with respect to the detector has a great influence on the results.

In this work, a simulation-based method for the characterization of the effect of system geometrical deviations on the accuracy of XCT dimensional measurements has been developed. The simulated object is a ball plate made of 56 ruby spheres, 49 of these placed in a 7x7 regular grid, of 1 mm diameter on a CFRP plate (see Figure 1a). A first simulated scan was carried out with the system ideally aligned and the measurements results were taken as reference. Angular misalignments of 0.5°, 1° and 1.5° were then simulated according to reference [6], for individually inspecting tilt, slant and skew. For each scan, the ball plate was placed as illustrated in Figure 1b: the projection of the central column and the central row of spheres lies respectively on the central column and the central row of the aligned detector and the projection of the central sphere on the center of the detector.

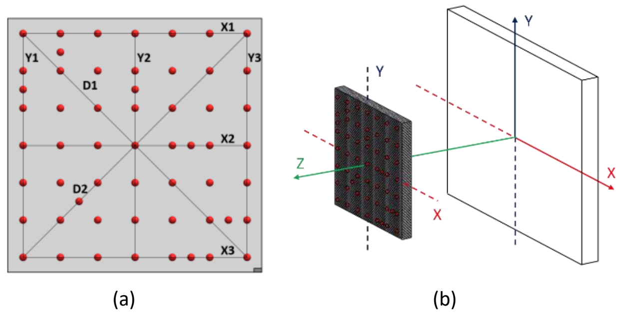

Figure 1. Ball plate used for the simulated XCT scans. The indicated directions are those considered for the measurements (a). Ideal system configuration for the reference simulation (b)

The simulations were performed using the software tool aRTist 2.0 (BAM, Germany), the reconstruction process was carried out using CTPro 3D (Nikon Metrology, UK), and both surface determination and sphere-to-sphere distance measurements were conducted using VGStudio MAX 3.1 (Volume Graphics GmbH, Germany).

3. Results

Results show that the errors (in absolute value) due to a slant of the detector in X direction and along the diagonals rises linearly for increasing distances, with slope that increases with the angle amplitude. Along the Y direction, the errors are randomly distributed and are smaller than 2 µm for the maximum considered angle (i.e. 1.5°). The errors measured along the X direction related to a tilt rotation are different in different areas of the detector: the distances measured in the central row exhibit errors smaller than 0.4 µm; the outer rows, which correspond to the top and the bottom part of the detector, are characterized by errors that have a similar linear trend with respect to the measured distances, but with opposite sign. This trend depends both on the distance from the central row of the detector and the amplitude of the angle, as shown in Figure 2 for direction X1.

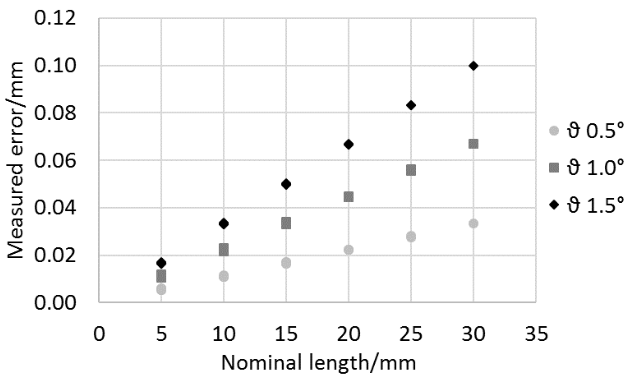

Figure 2. Sphere-to-sphere measurements errors along direction X1 for detector tilt of 0.5°, 1° and 1.5°

The maximum errors registered along the X direction are equal to 33.8 µm for a tilt of 0.5 °, 66.9 µm for a tilt of 1 ° and 100.3 µm for a tilt of 1.5 °. Considering the Y direction, the results have a trend that confirms the experimental observations presented in reference [7] but with larger deviations (see Figure 3): errors up to 16.6 µm, 31.4 µm, and 44.7 µm were detected respectively for 0.5°, 1° and 1.5°. The errors along the diagonals show a trend similar to the one obtained along Y direction. A skew of the detector leads to errors that seem to be independent from the specific investigated area of the detector and from the specific measured distance. Moreover, such errors do not exceed 1 µm for every angle amplitude tested.

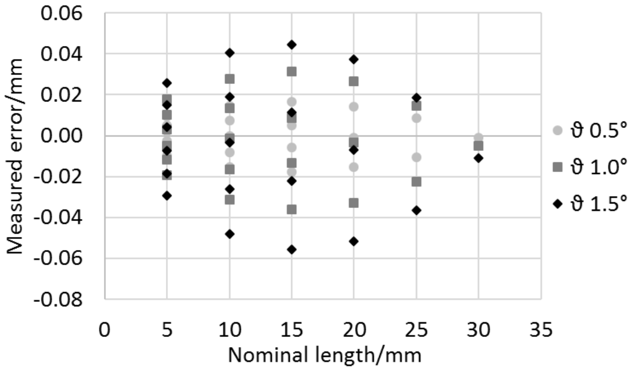

Figure 3. Sphere-to-sphere measurements errors along direction Y3 for detector tilt of 0.5°, 1° and 1.5°

4. Conclusions

In this work, the specific effect of different angular misalignments of the detector on XCT dimensional measurements of a ball plate (see Section 2) was evaluated. This is the first part of a simulation-based study that aims at characterizing the impact of any possible deviation from the ideal geometry of an XCT system on dimensional measurements, in order to develop a faster and easier method to control the geometry by focusing on the most critical factors. The center-to-center distances were measured on the ball plate along the X direction in the central and in the first and last rows of spheres, along the Y direction in the central and in the first and last columns of spheres as well as along the principal diagonals. In this way, the errors were mapped on the entire detector area.

Detector angular misalignments of 0.5°, 1° and 1.5° lead to results in agreement with simulation and experimental investigations presented in literature. Misalignments around the X-axis turned out to be the most critical, causing errors up to 100 µm. Future activities are planned to investigate the out of plane rotations, deepening the analysis for smaller angle amplitudes and focusing the attention on angular misalignments along the X-axis.

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