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A sensitivity analysis of the rotation stage misalignments effect on X-ray computed tomography dimensional measurements

E. Sbettega[1], F. Zanini[1], S. Carmignato[1]

[1]*Department of Management and Engineering, University of Padova, Vicenza, Italy*

elia.sbettega@phd.unipd.it

Abstract
X-ray computed tomography (CT) is increasingly used in manufacturing metrology thanks to its advantages including the capability of performing non-destructive measurements of both accessible and non-accessible complex geometries. However, the accuracy enhancement of CT-based measurements still represents a major challenge due to the complexity and large number of influence factors. This work is part of a study focused on the enhancements that are achievable by monitoring and correcting the system geometry, through the inspection of several parameters describing the relative position and orientation between the hardware components. In particular, the work has been planned to achieve a complete knowledge and comprehension on the geometry-dependent effects on CT results in order to develop a fast and easy-to-implement procedure for CT systems geometry characterization and correction. At the scope, a 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 investigated and corrected. This work is focused on the specific effect of rotation stage misalignments, which were investigated separately from the other possible geometrical misalignments.

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

1. Introduction

The increasing need of inspecting and measuring in a non-destructive way complex parts with free-form shapes and features non-accessible from the outside is at the basis of the growing use of X-ray computed tomography (CT) in manufacturing metrology. However, the accuracy enhancement of CT-based measurements still represents a major challenge due to the large number of influence factors. The system geometry represents one of the most critical influence factors. The most common architecture of industrial CT systems used for metrological purposes employs three major components: (i) an X-ray source emitting an X-ray cone beam, (ii) a motion system equipped with a rotary stage and (iii) an X-ray detector. The relative position between these components must respect strict alignment conditions to avoid errors in the reconstructed volumes [1]. For this reason, a number of methods have been proposed to characterize the system geometry and to investigate the effect of possible geometrical misalignments [2, 3]. However, such methods need to be optimized, in order to reduce time consuming and difficult to implement procedures.

The present work is a part of a wider study focused on the geometrical characterization of CT systems. The final aim of the study is to provide a complete understanding of the effect of each possible geometrical misalignment on dimensional measurements in order to develop fast and easy-to-implement procedures for the system geometry characterization and correction.

2. Simulations setup and analysis workflow

A simulation routine was developed to characterize the effects of geometry deviations of cone-beam CT systems on the accuracy of dimensional measurements. The specimen designed to be used in the simulation process is a ball plate composed of 56 ruby spheres of 1 mm diameter arranged on a CFRP plate (see Figure 1a). In this work, 49 spheres placed in a regular 7×7 grid, equally spaced by 5 mm were considered. The simulation routine and the ball plate – used in a first part of the work to study the effect of detector angular misalignments [4] – are used here to investigate the impact of rotary table misalignments, including angular misalignments (ϑ with respect to X-axis, η with respect to Z-axis) and linear shifts (Δx, Δy) (see Figure 1b). Such misalignments were simulated starting from the aligned configuration, for which the ball plate is placed with the column Y2 and the row X2 (see Figure 1a) respectively projected on the central column (along the vertical Y-axis) and on the central row (along the horizontal X-axis) of the detector. The misalignment-related nominal values, reported in Table 1, were selected in order to compare the impact of rotation stage deviations with detector deviations analysed in a previous part of the work [4]. The simulations were performed using the tomosynt module of the software tool aRTist 2.0 (BAM, Germany). The projection data were elaborated using the commercially available reconstruction software CTPro 3D (Nikon Metrology, UK), using the filtered backprojection algorithm. The surface determination and the dimensional measurements (i.e. center-to-center distances and spheres form errors) were conducted using the analysis and visualization software VGStudio MAX 3.2.3 (Volume Graphics GmbH, Germany).

Table 1 Tested values for rotation stage misalignments.

Misalignments	Tested nominal values
ϑ	0.01°, 0.02°, 0.05°, 0.1°, 0.2°, 0.3°, 0.4°, 0.5°, 1.0°, 1.5°
η	0.5°, 1.0°, 1.5°
Shift Δx / mm	0.3, 0.5, 3.0
Shift Δy / mm	0.3, 0.5, 3.0

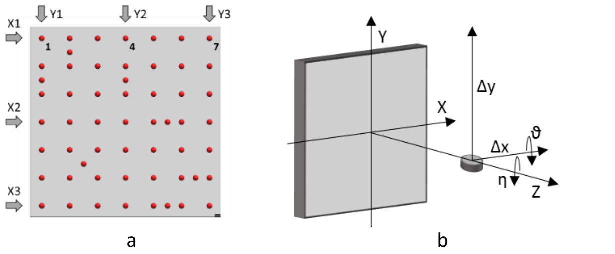

Figure 1. Ball plate designed for the simulation study (a). Scheme of the misalignments investigated in the work (b).

3. Results

The analysis of the impact of angular deviations demonstrated that the tilt of the rotation stage around the X-axis (ϑ) is the most critical misalignment. The resulting center-to-center measurement errors – along both X and Y directions – showed trends similar to that caused by the corresponding detector tilt [4]. For example, the maximum deviations registered along column Y2 were equal to 17 µm for a rotation tilt ϑ = 0.5°, 35 µm for ϑ = 1.0° and 55 µm for ϑ = 1.5°. Similar results were obtained along rows Y1 and Y3.

Center-to-center measurement errors along the X direction were observed to be strongly dependent form the measured distance and from the investigated region of the detector. For example, the errors evaluated along row X1 on the upper region of the detector (see Figure 2) increase with the measured distance and become more relevant for higher angle amplitudes. Errors up to 26 µm, 57 µm and 62 µm were measured for ϑ equal to 0.5°, 1.0° and 1.5°, respectively.

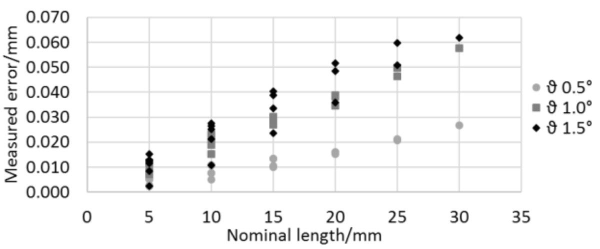

Figure 2. Center-to-center measurement errors along direction X1 for tilt (ϑ) equal to 0.5°, 1° and 1.5°.

The deviations measured along the row X3, which lies on the lower region of the detector, have a similar but symmetric trend. In row X2, the deviations were found to be less critical, reaching the maximum value of 4 µm for ϑ = 1.5°.

Smaller ϑ angles, down to 0.01°, were also investigated to increase the understanding about the impact of such kind of rotation stage tilt on the measurement accuracy. Figure 3 shows the maximum errors determined for each measured distance (from 5 to 30 mm), calculated along row X1. The impact of the tilt ϑ increases with the angle amplitude and starts to be significant from angle amplitude of 0.1°, with errors up to 3 µm.

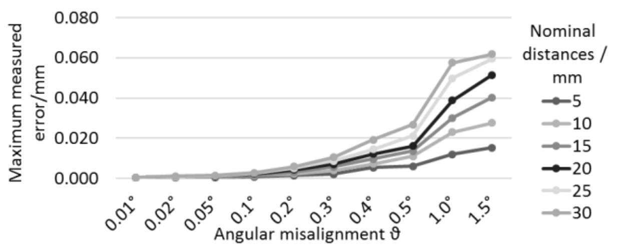

Figure 3. Maximum center-to-center measurement errors along direction X1 for each tested amplitude of the angle ϑ.

Figure 4 shows the form error evaluated for sphere 1, 4 and 7 (indicated in Figure 1a), varying the tilt magnitude. Starting from ϑ = 0.1°, there is a significant increase of the form error of sphere 1 and 7, while the form error of sphere 4 (that lies in the central column Y2) remains similar for all the angle amplitudes tested.

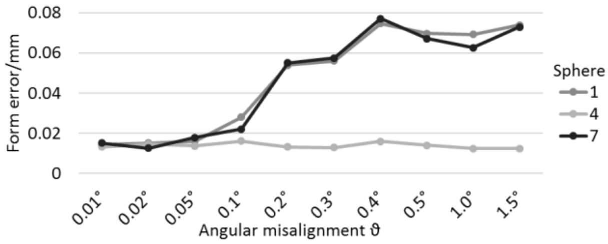

Figure 4. Form errors of sphere 1, sphere 4 and sphere 7, for each tested amplitude of the angle ϑ.

Angular misalignments around the magnification axis (*η)*, as well as shifts along the X and the Y direction (*Δx, Δy*), showed less significant trends of the measurement errors with respect to the specific investigated region of the detector or to the measured distance. In these cases, the deviations did not exceed 1 µm in each direction for all the misalignments tested.

4. Conclusions

In this work, the impact of rotation stage misalignments on CT dimensional measurements was investigated through a new simulation setup. The work is part of a wider study focused on the characterization of the effect of each geometrical misalignment of CT systems on the accuracy of dimensional measurements. A ball plate was designed and a simulation routine was developed in order to measure the center-to-center distances along different directions (see Figure 1) in different regions of the detector. The tilt around the X-axis was found to be the most critical rotation stage misalignment. The effect on the measurement of center-to-center distances was found to be comparable to the effect of the corresponding detector tilt, for angle amplitudes of 0.5°, 1.0° and 1.5°. An investigation of smaller angle amplitudes highlighted that the effects of a tilt of the rotation stage become significant starting from an angle amplitude of 0.1°, both for center-to-center distances, with errors up to 3 µm, and form errors. Future activities are planned to evaluate the impact of the spheres identification on the center-to-center distance and to investigate the effect of possible interactions between geometrical misalignments of detector and rotation stage, as well as to experimentally validate the results.

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