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Experimental investigation on the influence of detector misalignment on X-ray CT measurement accuracy

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Abstract
In X-ray computed tomography (CT), measurement accuracy and image quality are strongly affected by the presence of geometrical misalignments and/or the wrong estimation of CT system geometry . In this work, the effects of detector misalignment are experimentally investigated. CT measurements of a calibrated ball bar were acquired first with the system aligned according to the manufacturer's guidelines, and then after that the flat-panel detector was physically misaligned. The experimental results were compared to show the effects of detector misalignment on CT measurement errors.

Computed tomography, dimensional metrology, detector misalignment, measurement accuracy

1. Introduction

X-ray computed tomography (CT) has high potential for advanced dimensional quality control in industry [1]. However, in order for CT systems to be fully recognized as coordinate measuring systems (CMSs), CT measurements must be traceable to the unit of length. One essential step towards traceability of CT measurements, is the correct estimation of the actual CT system geometry which is a crucial requirement for accurately performing the tomographic reconstruction and, then, all the following analyses on the reconstructed volume [2]. The system geometry may be estimated directly from images of specific phantoms, (e.g. [3,4]), or fed into the reconstruction routine as the result of the mechanical calibration of all axes of the system. The wrong estimation of the system geometry and/or the presence of geometrical misalignments not accounted for during the reconstruction can have a strong impact on the reconstructed volume, leading to artifacts and measurement errors when performing metrological tasks. Hence, the effects of system geometry misestimations or geometrical misalignments on CT measurement accuracy must be determined.

Kumar et al. [5] and Ferrucci et al. [6] showed, by means of simulations, how geometrical misalignments and other errors on CT system geometry may have significant effects on dimensional measurements; however, no information is there provided on data based on experiments. This work focuses on the experimental investigation of a particular type of system misalignments: detector misalignment. The results obtained with the system aligned according to the manufacturer's guidelines are compared with the results obtained with a purposefully physically misaligned flat-panel detector. The experimental results show the effects of detector misalignment on CT measurement results.

2. CT system geometry

In order for a CT system to be correctly aligned, the following constraints must be respected. Ideally, the X-ray source, the center of rotation and the detector center are positioned on a straight line, which coincides with the central ray. This line also is perpendicular to the detector surface and intersects the detector on its center. The rotation axis is perpendicular to the central ray, and its projection is parallel to the detector columns. However, in a real system residual errors between the three components could be present, causing a system geometry which differs from the ideal situation.

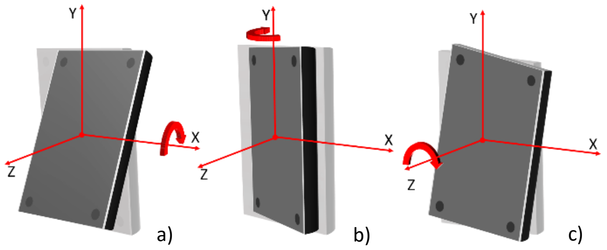

Figure 1. Schematic representation of detector angular misalignments: detector pitch a), detector yaw b), detector roll c). The aligned detector is represented in light grey, the misaligned detector in dark grey.

In particular, in Figure 1 three different possible detector angular misalignment are represented, and compared to the ideally aligned position of the detector (represented in light grey color). Detector pitch and detector yaw (respectively about the *X* and the *Y* axis of the detector) are out-of-plane rotations. Detector roll about the *Z* axis, produces an in-plane rotation. Rotations can occur also about axis different than the detector central axis represented in Figure 1, and can be combined together. These types of rotations can be interpreted as a superimposition of the detector rotations represented in Figure 1, and detector translations.

3. Experimental investigations and results

In this work, the influence of detector out-of-plane rotation about the *X* axis are studied. First, CT scans of a calibrated ball bar were acquired with the system aligned according to the manufacturer's guidelines. Sphere distance errors (i.e. sphere center-to-center distances), diameter errors and form errors were calibrated by tactile CMM measurements and then CT measured, to investigate the residual errors present with the CT system properly aligned. The ball bar used for the analysis consisted of 7 equally spaced spheres (with nominal diameter equal to 1.59 mm, and center-to-center nominal distances ranging from 5 mm to 30 mm) was oriented in the vertical direction of the CT system (i.e. parallel to the *Y* axis of Figure 1) and placed off-center from the center of rotation. Moreover, sphere 4 was positioned approximately on the detector central plane in the aligned configuration, whereas sphere 1 and 7 were positioned respectively close to the upper and lower edge of the detector.

The flat-panel detector was purposefully physically misaligned for studying the influence of a rotation about the *X* axis. Three angular misalignments of 0.5°, 1° and 1.5° (nominal values) were induced in the detector in the direction represented by the arrow in Figure 1-a. For each misaligned configuration, one scan was acquired with the ball bar oriented in the same way as for the reference CT scans. For each scan, a procedure to estimate the geometry of the system was applied as per the system manufacturer's guide. In this procedure, out of plane rotation of the detector was disabled from the geometry estimation. Therefore, the detector misalignment about the *X* axis was not accounted for, whereas magnification errors at the center of the detector were taken into account. After reconstruction, all CT data were imported and analyzed using VGStudio MAX 3.0 and a local adaptive surface determination was applied for all CT scans. Figure 2 reports the sphere distance errors obtained for the experimental investigations. Standard deviations smaller than 0.4 µm were found for the reference scans in the aligned configuration.

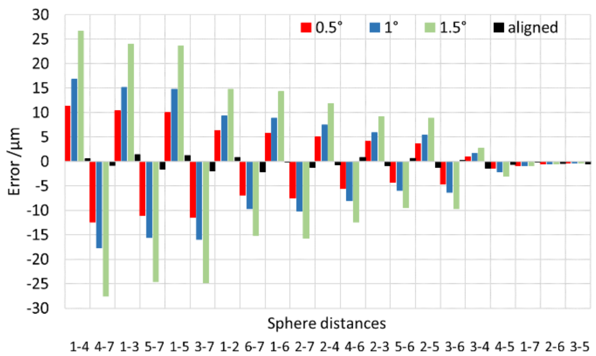

Figure 2. Sphere distance errors between the seven spheres of the ball bar. The measured errors (CT values – CMM values) are plotted for the aligned and misaligned configurations.

For a detector misalignment of 0.5°, sphere distance errors up to 12 µm are present. When increasing the amplitude of the misalignment to 1° and 1.5° the errors also increase and reach respectively 18 µm and 28 µm. Compared to the aligned configuration, therefore, the induced misalignments produce a significant increase of sphere distance errors. As expected, moreover, the measurement errors increase with increasing amplitudes of the angular misalignments. Figure 2 also shows how, for the three angular misalignments investigated, the sphere distance errors present a specific symmetric behavior about the *X* axis. Distances between spheres positioned above the central plane of the detector in the aligned configuration present positive errors, whereas distances between spheres positioned below the central plane present negative errors. For example, the sphere distance error between sphere 1 and 4 is similar to the one between sphere 4 and 7 but with the opposite sign. The magnification, in fact, is established at the center of the detector and the angle introduced affects the magnification symmetrically about the detector center. In particular, the source to detector distance (SDD) is affected in opposite directions. With respect to the aligned configuration, for the induced misalignments, SDD increases for spheres above the central plane of the detector and it decreases for spheres below. This means that magnification errors are present which increase for spheres far away from the center of the detector in the aligned configuration. As visible in Figure 2, the lengths which comprise points symmetric about the *X* axis are characterized by a smaller error because they have opposite errors that cancel out; for example this happens for sphere distance 1-7.

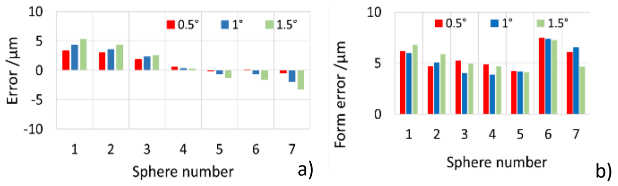

Figure 3. a) Diameter errors (CT values – CMM values) for the seven spheres of the ball bar. b) Form errors.

Figure 3-a shows the results obtained for the diameter errors. Also in this case the errors increase with the amplitude of the misalignment and reach 5.3 µm for the 1.5° misalignment; moreover, spheres which occupy similar regions on the detector in the aligned configuration, but at opposite sides vertically, show diameter errors with opposite signs. Figure 3-b reports the form errors obtained for the misaligned configurations. Similar results were found with the system aligned. Therefore, the effect of the investigated misalignments on form errors is negligible.

4. Conclusions

Three angular misalignments of 0.5°, 1° and 1.5° were physically induced on a flat-panel detector for studying the effects of an out of plane rotation about the *X* axis. The experimental results showed that a detector misalignment about the *X* axis has a significant effect on center-to-center measurements performed in the vertical direction. In particular, detector pitch produces a specific pattern on sphere distance errors, caused by magnifications errors. For all the investigated detector pitch up to 1.5°, magnification errors symmetric about the *X* axis were found, which increase for spheres far away from the center of the detector in the aligned configuration. When increasing the angular misalignment, the measurement errors consistently increase. For diameter errors, it was also found that spheres which occupy similar regions in the aligned configuration but at opposite sides vertically, show diameter errors with opposite signs. For detector pitch up to 1.5°, the effects on form errors were found to be negligible. Future works will deal with the analysis of the influence of different sample orientation and detector misalignments.

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