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Investigation on scan parameters for accurate dimensional measurements by CT helical scanning

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Abstract
In industrial X-ray computed tomography (CT), conventional scans using circular trajectories face limits when dealing with internal and complex features on elongated workpieces, mainly due to the dimensions of the detector. To this extent, helical scanning is a powerful solution that enhances flexibility of the system and, when using suitable parameters, enables obtaining a strong improvement on image quality, eliminating the cone-beam artifacts that characterize conventional scans. In this work, metrological performances in CT helical scanning are experimentally investigated and compared with those of conventional circular scans. The influence of main helical scan parameters are studied to enhance accuracy of dimensional measurements by CT helical scanning.

Keywords: X-ray computed tomography, helical scanning, dimensional measurements, metrological performance verification, accuracy

1. Introduction

X-ray computed tomography (CT) is increasingly used in industry as a high potential non-contact technique for dimensional metrology [1]. Besides its well-known applications in the medical field, and for non-destructive testing (NDT), it enables to perform a multitude of measuring tasks that in many cases are not possible with traditional coordinate measuring machines (e.g. tactile and optical CMMs) [2, 3]. When dealing with internal and complex features on elongated workpieces, traditional CT scans that use circular scan trajectories face limits, mainly due to the dimensions of the detector, and the desired resolution [4]. A powerful solution is the use of CT helical scanning trajectory, also known as spiral CT [1]. This technique enables the analysis of long objects exceeding the dimensions of the detector along the rotation axis in one single scan, and significant improvements on image quality. In order to use CT systems that exploit helical scan trajectories as coordinate measuring systems, the metrological performance and influence of scanning parameters on measured characteristics must be determined. In [5] the authors investigated the metrological characteristics probing errors of size and form (respectively *PS* and *PF*), as described in VDI/VDE 2630-part 1.3 [6], on a simulated helical scan dataset. In that case, helical scanning provided significantly lower *PF* compared to conventional circular scans, however no experimental validation was there provided. In [7] a 10x10x10 mm^3 titanium alloy cube featuring several spherical calottes was scanned, simulated helical scan results and real data, in this case did not agree. In the present work, metrological performances of CT helical scanning are experimentally investigated and compared with those of conventional circular scans. A design of experiments (DoE) is executed to investigate the influence of the main helical scan parameters. Experimental results prove that CT helical scanning performs better than conventional circular scan trajectories, especially while dealing with form measurements. An optimization of helical scan parameters for CT helical scanning accuracy enhancement is proposed.

2. Material and methods

In CT helical scanning the rotation of the object is simultaneously performed with a translational movement along the rotation axis. The translational movement can be obtained either by moving the manipulator along the direction of the rotation axis, or with a combined movement of source and detector. From a fixed point in space, the trajectory of a point belonging to the object describes a helix. The use of helical trajectories, therefore, enables analyzing long objects, exceeding the dimensions of the detector along the rotation axis, in one single scan. Moreover, shading and streaking artifacts (i.e. cone beam artifacts) due to incomplete sampling [8], which increase in conventional circular scans while moving away from the central plane of the detector and with cone-beam angle, can be eliminated when using an appropriate helical pitch (i.e. distance travelled per revolution), leading to significant improvements of image quality. On the other hand, additional motion is required, which could lead to additional error sources for metrological applications. In this work, a scanning set-up with the manipulator moving along the vertical direction, stationary X-ray source and detector was used.

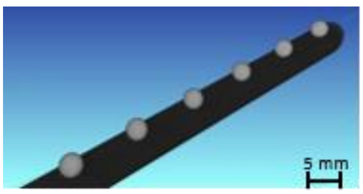

Figure 1. Calibrated reference object used for the investigation.

The reference object shown in Figure 1 was scanned in the vertical orientation. It consists of a ball bar featuring six ruby spheres, with nominal diameter of 3.18 mm, glued on a carbon-fiber rod. Sphere diameters and 15 uni-directional lengths (i.e.

center-to-center distances) were calibrated by means of repeated tactile CMM measurements.

3. Experimental results

CT scans were performed with a NSI CXMM metrological CT system, with a 225 kV micro-focus X-ray source and air-cooled cabinet. Three repeated circular CT scans were performed with a voxel size of 33.6 µm, and a cone-beam angle of 25.6 degrees, acquiring 1080 projections. A 3^2 factorial design was set for the helical scans, with scanning parameters of Table 1.

Table 1. Scanning parameters used in the DoE for helical scans.

Factors	**Levels**		
Helical pitch	3.1 mm	5.6 mm	14.0 mm
Nr. projections	1080	2500	4000

Each scan was performed with every combination of helical pitch and number of projections, for a total of 9 helical scans. An adapted FDK algorithm was used for helical scan reconstruction. Experimental results were then analyzed by means of VGStudioMAX 2.2. Probing errors of size and form, *PS* and *PF*, and sphere distance errors, *SD*, were calculated according to VDI/VDE 2630 part 1.3. Experimental results showed that there is no significant difference between *PS* and *SD* for circular and helical scans, which are always within 3 µm and 4 µm respectively. For traditional circular scans, measured *PF* strongly depend on the position of the spheres on the detector. The form measurements range approximately from 6 µm (for spheres in the central plane of the detector) to 25 µm for sphere at top and bottom of the detector, where cone-beam artifacts have a stronger influence. When using helical scanning trajectories, a significant improvement on *PF* is obtained. In this case *PF* are always homogenously distributed along the whole detector regardless of the used helical pitch and number of projections. For all 9 helical scans, the trend for *PF* is almost a horizontal line.
Figure 2 describes the influence of helical pitch on measured *PF*.

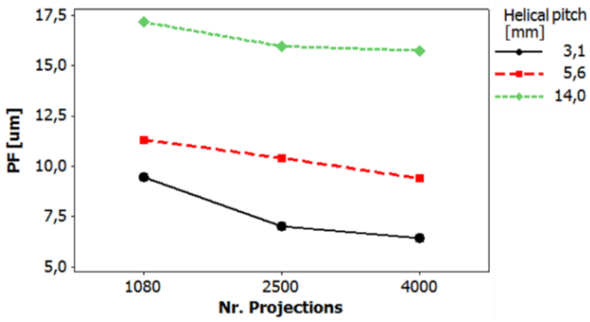

Figure 2. Influence of helical pitch on measured *PF* for helical scans.

As expected, the pitch has a high influence. With a helical pitch of 14.0 mm, which is more than 4 times the diameter of the spheres, probing errors of form are on average 17.5 µm. With a smaller helical pitch of 5.6 mm, *PF* are significantly lower reaching 9 µm. The smallest helical pitch of 3.1 mm provides the best results. In this case, *PF* is comparable with the one obtained with circular scans for spheres in the middle plane of the detector. For helical scans, however, the probing error does not depend on the sphere position on the detector. In Figure 3, the dependency of measured *PF* and number of projections is reported. The number of projections has a lower effect compared to the helical pitch. For all the three chosen helical pitches, increasing the number of projections decreases *PF*. This effect is more significant when using a smaller pitch, which means an increased number of revolutions, and therefore a smaller number of projections per revolution (with fixed number of projections). Comparing the values obtained using a 14.0 mm pitch and 4000 projections, and those using a 5.6 mm pitch and 1080 projections, differences around 4 µm are obtained. Scanning times in the latter case are significantly reduced. This suggests decreasing the helical pitch (which increases scanning time) to a value similar to the dimension of the characteristic to be inspected, and decreasing the number of projections (which decreases scanning time) to a suitable value for the given helical pitch, avoiding undersampling.

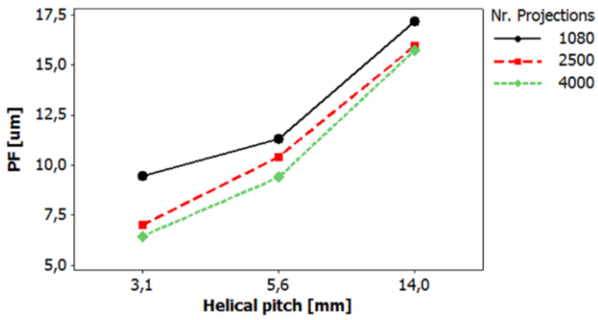

Figure 3. Influence of number of projections on *PF* for helical scans.

4. Conclusions

Metrological performances of CT helical scanning have been evaluated by means of repeated CT scans on a calibrated reference object. Experimental results proved that helical scanning can perform better than conventional circular scanning, even though additional movements of the manipulator are required. Strong improvements can be obtained especially while dealing with form measurements. When using an appropriate helical pitch, values comparable with those obtained with circular scans for the spheres in the middle plane of the detector are achieved. For helical scanning however, *PF* are always uniformly distributed along the whole detector. The helical pitch has a strong influence on measured *PF*, whereas the influence of number of projections increases with a smaller helical pitch. By using a helical pitch of the same dimensions of the characteristics to be inspected, a significant enhancement of helical scanning accuracy is achieved.

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