euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023
www.euspen.eu

Estimation of optimal sample orientation for accurate industrial computed tomography scanning

Ibon Holgado[1], Naiara Ortega[1, 2], Soraya Plaza[1, 2], José A. Yagüe-Fabra[3], Herminso Villarraga-Gómez[4]

[1] *Aeronautics Advanced Manufacturing Center (CFAA), Parque tecnológico de Bizkaia, 202, 48170 Zamudio, Spain*
[2] *Department of Mechanical Engineering, Aeronautics Advanced Manufacturing Center (CFAA), Faculty of Engineering of Bilbao, Plaza Ingeniero Torres Quevedo 1, 48013 Bilbao, Spain*
[3] *I3A, Universidad de Zaragoza, María de Luna 3, E-50018 Zaragoza, España*
[4] *Carl Zeiss Industrial Quality Solutions, LLC, Wixom, MI, USA*

Ibon.holgado@ehu.eus

Abstract

One strategy that can allow an improvement in the quality of an industrial computed tomography (CT) image is finding an optimal specimen orientation for measurement. This implies to fix the specimen in an orientation that, for instance, minimizes the penetration lengths of the X-rays through the object material and avoid sharp thickness variations during the complete CT scan. However, when the geometry become complex (with hidden areas, large cumulation of thicknesses, etc.), the optimal orientation is rarely achieved even by experienced CT operators. To address this issue, a software tool which estimates the optimal orientation automatically is presented in this work. Accordingly, a mathematical function, called score, which prioritises and assigns different weights to the variables that affect most the CT data quality is proposed. Experimental CT measurements are contrasted with score values, and a relation between a CT data quality metric (contrast-to-noise-ratio), score values, and CT measurements accuracy, is presented. The results show that the CT measurement accuracy is, in all the evaluated measurands, affected by the orientation of the part in the rotatory table, altering results by up to an order of magnitude in some cases. In addition, the software tool provides a 3D score map for each evaluated orientation (which is configurable) and the results show how the "best orientations" produce less dispersion in the results, i.e. more stability in the scanning process.

CT, orientation, measurement, accuracy, experimental

1. Introduction

Computed tomography (CT) is becoming a more and more accepted measurement method by the non-destructive testing community as it facilitates both qualitative and quantitative inspections of the complete specimen in a single scan [1]. Given its potential for quality control, the use of CT is growing in industries such as aerospace, aeronautics, and automotive, where the safety is a must. All these technologies share the need to ensure that data provided by CT scan are as accurate as possible. Unfortunately, there are still many aspects regarding CT image quality that need to be understood (e.g., the influence of the appearance of artifacts on CT measurements results) [2].

One strategy which may allow improvement in CT voxel data quality is finding an optimal specimen orientation for CT scanning. A good practice for an adequate orientation implies to fix the specimen in an orientation that, for example, minimizes the penetration lengths of the X-rays through the object material and avoid sharp thickness variations during the complete CT scan [3]. Yet, when the geometry becomes complex (with hidden areas, large cumulation of thicknesses, etc.), the optimal orientation is rarely achieved even by experienced CT operators. Unfortunately, this often involves scanning the parts multiple times to find the optimal orientation, which results in long machine occupation times and high costs.

Recently, some attempts have been made to try to optimise the orientation of workpieces in CT. In this context, results of CT process simulation methods are widespread. However, these methods are generally focused on the optimisation of all CT scanning parameters, and it is necessary to run a complete data acquisition and processing procedure for each set of parameters to be tested [4]. Moreover, there is still a lot of work to be done to verify the reliability of the results of several emergent simulation tools (e.g., the software 'aRTist' [5]), mainly because their correlation with experimental data still have room for improvement. This software solutions seek to optimize the CT scan process overall parameters and variables, which is challenging given the inherent complexity of X-ray behaviour through matter [4]. Therefore, they require manual input of a large number of CT process parameters, often in not user-friendly interfaces, and this requires experienced CT operators and time-consuming simulation set-up. Other approaches use only the information about the geometry of the specimens to automatically determine the optimal orientation [6]. However, no clear conclusions are drawn on the impact of the proposed orientation results on the CT measurements accuracy.

Some studies have attempted to relate CT image quality to the accuracy of CT measurements. For example, to address this gap in the field of dimensional CT metrology, the same authors in a previous investigation [7] discussed the relationship between spatial resolution and contrast sensitivity in CT scans of different materials on the accuracy of the resulting CT measurement results. Experimental results showed a strong relationship between contrast-to-noise-ratio (CNR) and CT measurement accuracy for a large number of samples of different materials. Other studies follow the above agreement, pointing out that contrast, foreground (material) noise and background noise influence together the surface determination operation and thus CT dimensional measurements [8].

In this work, a software tool that automatically estimates the optimal orientation of a specimen is developed. This study focuses on the influence of different statistical weighting factors that represent the X-ray penetrations lengths and thickness variations in different specimens. Accordingly, a multi-objective optimization is suggested. It prioritizes and assigns different weights to the variables that most affect the quality of the CT results. The proposed tool works merely with information about the geometry of the workpiece, avoiding the complex nature of CT process, as well as the uncertain influence of the parameters of the scanning set-up on the final result. The predicted optimal orientations are validated through different samples geometries. Furthermore, a straightforward relation between predicted orientations, CNR, and CT measurements accuracy, is presented.

2. Materials and methods

This section presents the framework developed to estimate the optimal orientation on different real-world parts. To do so, the details of the evaluated parts and the CT setting parameters used in the experimental tests are presented in Section 2.1, the description of the workflow of the proposed software tool is described in Section 2.2, including the mathematical optimisation that governs it, and the specific details related to the calibrated characteristics used to evaluate the influence of orientation on the accuracy of CT measurements are detailed in Section 2.3.

2.1. Specimens and CT scans

A total of two real-world parts were analysed to estimate the optimal orientations and validate the effectiveness of the digital model. Test specimen one, an impeller, is a real industrial aluminium component. This part contains different complex geometries that produce cumulative thicknesses not obvious even to an experienced CT operator (Figure 1(a)). Test specimen two is a tool test artefact that contains a set of calibrated characteristics and is used to evaluate the influence of orientation on the accuracy of CT measurements (Figure 1(b)).

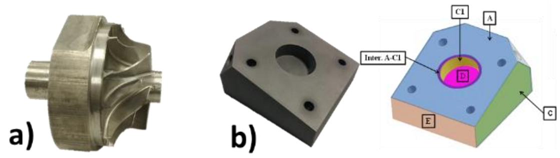

Figure 1. Test parts a) impeller and b) tool test artefact and CMM measured geometric elements.

All parts were made of aluminium, one of the most widely used materials in different industrial sectors, ensuring easy penetration of X-rays and offering good dimensional stability ($\alpha \approx 23.8$ µm m-1 ◦C-1). Experimental tests were carried out in a cone-beam projection system with circular-orbit trajectory, a General Electric X-Cube Compact machine. The source voltage was selected to ensure that all evaluated objects are always penetrable, regardless of their orientation. Under these criteria, the voltage was adjusted to 175kV. Then, the tube current value was chosen to be high enough as it leads to a reduced exposure time, allowing the least scanning time without decreasing the image contrast/brightness. This resulted in 3.4 mA and 100 ms of exposure time. The combination of 1 mm copper and 0.5 mm tin filters achieved a homogenization effect of photons energy that reached the workpiece, minimizing the beam hardening effect. The placement of the specimens on the rotatory table was carried out with polyethylene foam, providing a minimal influence when scanning an object. Polyethylene foam can easily be obtained and cut using a conventional cutter (to place the parts in the orientations predicted by the model) and is a rigid material that allows the sample placement to remain stable during scanning.

2.2. Description of the software tool

Using the workflow described in Figure 2, X-ray projection simulations were obtained for all possible orientations, using an adjustable angular step width in a virtual environment generated using the Python language. The orientation of the specimen is defined by two degrees of freedom, α for the rotation around the x-axis, and β for the rotation around the y-axis. As the specimen rotates during the scanning process, is not necessary a third angle to define the scanning orientation.

The first stage of the workflow is to load the specimen CAD data, and then discretize its volume into voxels (of a configurable size) to work with a 3D array, allowing elementary rotations. Then, the 3D array is rotated around the x-axis (at the selected angular step). For each α rotation, it also rotates 360° around the y-axis (at the selected angular step), as shown in Figure 2. In this way, all possible orientations in space can be achieved. Each rotation around x and y axes are defined by the rotation matrix. For more details on the mathematics used for 3D matrix rotations, or rotation around an arbitrary axis, refer to the Rodrigues rotation formula [9].

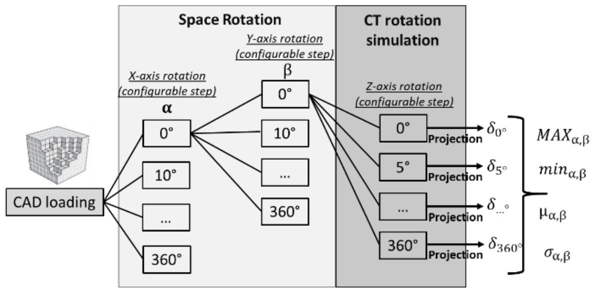

Figure 2. Workflow of the proposed model

For each iteration of specimen rotation around the x and y axes, the CT scan rotation, i.e. the revolution around the z-axis, is simulated, also at a configurable step. At each step of the z-axis rotation, as in the CT process, projections of the volume on the plane simulating the detector are obtained, as shown in the example of Figure 3. Each projection represents the number of voxels projected at each pixel position, thus, indicating the X-rays penetration lengths through the specimen at each pixel location.

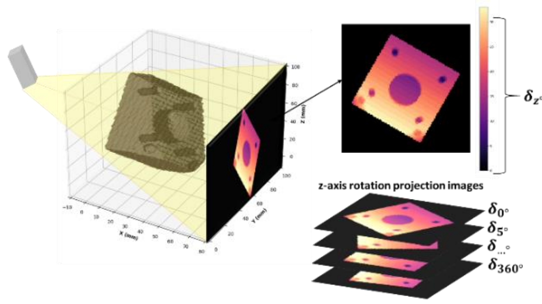

Figure *3.* Random α and β tool test artefact orientation in the generated Python environment. On the right side, a projection illustration with $\delta_{z°}$ examples.

Afterwards, the average of the pixels ($\delta_{z°}$) with non-zero values is obtained for all step projections in the revolution around the z-axis (for each α and β combination). Finally, different statistical metrics are extracted from the pixel averages ($\delta_{z°}$). In this study, the maximum penetration length ($MAX_{\alpha,\beta}$) was considered as the maximum value of all $\delta_{z°}$, the average penetration length ($\mu_{\alpha,\beta}$) as the mean value of all $\delta_{z°}$, the minimum penetration length ($min_{\alpha,\beta}$) as the minimum value of all δ_{z° and the penetration length variations (i.e. thickness variations) during the complete rotations about the z-axis ($\sigma_{\alpha,\beta}$) as the standard deviation of all δ_{z°. These variables were considered to be representative of the physical factors that affect most the CT image quality and with which the experienced CT operator usually tries to cope.

Once the statistical variables have been extracted, a function called "score" is obtained, which assigns different weights to the above-mentioned variables. To date, and in the reviewed literature, it is not evident how to prioritize or weight of these variables. Thus, the major achievement and the main objective of this work is to estimate the optimal orientation of any part in an automatic and optimized way through an optimised score function. Therefore, the optimal orientation is defined as: the α and β values resulting from the optimised score function.

As many studies in the literature [4,6] define the penetration lengths as the variable with the greatest impact on scan quality, firstly, the test parts were scanned at the α and β values that presented a minimum, intermediate and maximum $\mu_{\alpha,\beta}$ in the simulations. Thus, considering the score equal to $\mu_{\alpha,\beta}$ in this first stage. However, the results were inconsistent with predictions, and there was no obvious relationship between $\mu_{\alpha,\beta}$ and the experimentally obtained CNRs. As seen in Figure 4, in the case of the impeller part, the orientation with the minimum value of $\mu_{\alpha,\beta}$ provided the lowest CNR.

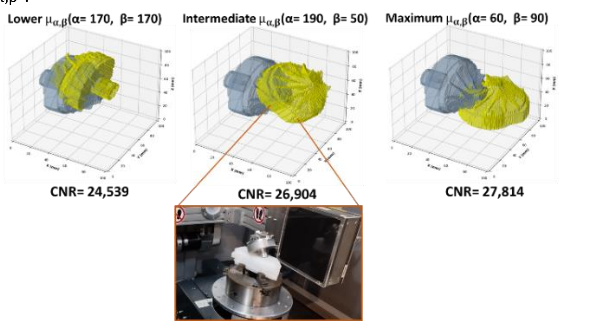

Figure 4. Minimum, intermediate and maximum $\mu_{\alpha,\beta}$ derived α and β orientations and experimental CNRs. The grey parts represent the loading orientation (the CAD orientation) and the yellow the rotated ones. At the bottom is an example of the placement on the rotatory table.

Given the previous incoherence, a score function was again defined to correlate with the experimentally obtained CNRs, this time combining all the statistical variables obtained in the simulation. For this purpose, the score function was mathematically optimized to achieve the function that offered the lowest mean squared error (between the score and CNR values for each orientation), being also a fundamental condition that an increase in the score leads to a decrease in the CNR. The score function was defined by assigning the following different weights to the statistical variables:

$$f^{score}(\alpha,\beta) = 0{,}78{*}\sigma_{\alpha,\beta} + 0{,}12{*}\mu_{\alpha,\beta} + 0{,}05{*}(MAX_{\alpha,\beta} - min_{\alpha,\beta}) + 0{,}05{*}MAX_{\alpha,\beta} \quad \textbf{(1)}$$

The highest weight was given to the $\sigma_{\alpha,\beta}$, as beam hardening and noise are among the most detrimental artifacts for image quality and are usually generated when the variance of the transmission length during rotation is large. The second highest weight was assigned to the average penetration length ($\mu_{\alpha,\beta}$), since the thinner the X-rays penetrate the more and better quality information the detector receives. Finally, the lowest weighting was assigned to the difference between the $MAX_{\alpha,\beta}$ and $min_{\alpha,\beta}$ and to $MAX_{\alpha,\beta}$ individually. Although this is the lowest weight, these variables are very important to evaluate because, when there is a very high thickness and there is a significant difference between the minimum and maximum thickness, artifacts derived from lack of penetration, streak artifacts and beam hardening are intensified. Figure 5 shows an example of the resulting 3D surface plot from the simulation of the optimal orientation of the impeller part. In the X and Y axis all the simulated scanning angles are shown (at a step of 10º) and in the Z axis the score in each case. The red cross indicates the optimal orientation.

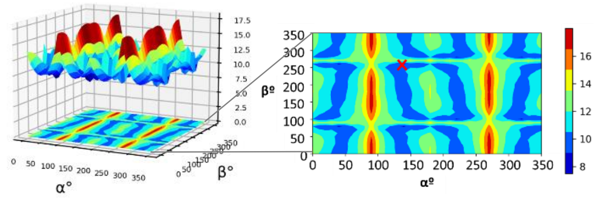

Figure 5. 3D surface plots obtained in the simulations.

2.3. Calibrated characteristics used to evaluate the influence of orientation on the accuracy of CT measurements

Different geometrical elements were measured using a Mitutoyo coordinate measuring machine (CMM), model Crysta Apex S-162012 with a maximum permissible error (MPE) equal to (4.5 + 5.5 L/1000) µm (where L is the length in mm) in the tool test artefact described in section 2.1. The measured geometrical elements are shown in Figure 1(b). All planes were fitted to the surfaces by means of Chebyshev outer and cylinder C1 by means of the maximum circumscribed cylinder.

To ensure the traceability of the CMM measurements the substitution method was applied, determining the measurement uncertainty using a procedure derived from ISO 15530-3. The measurement uncertainties attributed to the reference measurements are presented in Table 1. The selected measurements were specifically chosen to evaluate features of different magnitude at different positions on the part.

Table 1 CMM measurement results.

Characteristic	Measurand	CMM value (mm)	Expanded uncertainty (k=2) (mm)
Diameter	Cylinder C1 Max.circumscribed	39.8849	0.0023
Distance	Plane A from D	15.1037	0.0025
Angle (°)	Plane A from B	75.9121	0.0011
Perpendicularity	C1 from plane A L=C1	0.0029	0.0041

3. Experimental results

This section presents the comparison of obtained CT experimental data with CMM reference values as well as the resulted relations between the score and image quality for the tested samples. Figure 6 shows the score values obtained by equation 1 and the resulting CNRs for the evaluated parts. In this case, the orientations were the same as in the first stage and each specimen was scanned three times to assess the instability of the CT process.

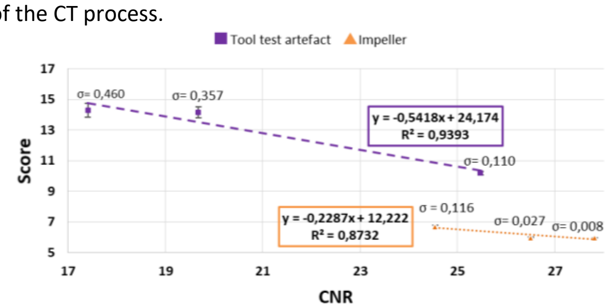

Figure 6. Relationship between score values and CNR results (experimentally obtained).

Figure 6 shows that the score can be related to the experimentally obtained CNR and that in all the evaluated cases a decrease in the score produces an increase in CNR with a near linear relationship. In addition, the dispersion between the results increased as the score value decreased. This indicates that the CT scanning process stabilizes as we approach lower scores and higher CNRs. Moreover, this relationship with CNR does not exist for any individual statistical variable, demonstrating the potential of the proposed combined function. Regarding the relation between the CNR and CT measurements accuracy, Table 2 summarizes the experimental CT values and the subsequent mean bias. For comparison with reference data, the measurement strategy with both CT and CMM was the same for each measurement.

Table 2 Experimental CT values, standard deviation (SD) and mean bias.

	Score	CT value	SD	Bias
Diameter (mm)	10.195	39.880	0.036	- 0.005
	14.153	39.771	0.038	- 0.114
	14.280	39.283	0.258	- 0.601
Distance (mm)	10.195	15.108	0.005	0.005
	14.153	15.113	0.004	0.010
	14.280	15.122	0.003	0.019
Angle (°)	10.195	75.935	0.006	0.023
	14.153	76.003	0.005	0.091
	14.280	76.011	0.008	0.099
Perpendicularity (mm)	10.195	0.019	0.015	0.016
	14.153	0.109	0.045	0.106
	14.280	0.170	0.073	0.168

From the results in Table 2 it can be concluded that the CT measurement results were in all cases affected by the scanning orientation, altering their value (e.g. in the case of perpendicularity) up to one order of magnitude. Furthermore, in all the cases evaluated, the following relationship was obtained: when scanning with angles (α and β) that offer a lower score, a higher CNR values are obtained, and in all evaluated measurands, a lower bias. This evidence the importance of the orientation in the scan set-up. Additionally, it is remarkable how the influence of noise is the major influence on the deviations obtained in Table 2, and, therefore, it is possible to relate the CNR metric to the accuracy of the CT measurements. Figure 7 shows an illustration of this effect. It shows a nominal-actual deviation analysis on the H1 hole of the part described in Figure 1(b), using a CAD of a regular cylinder with the nominal diameter.

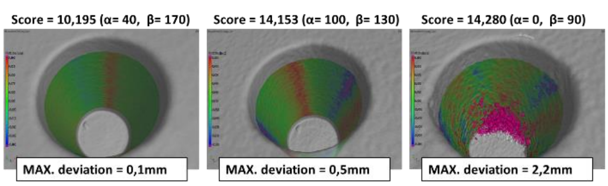

Figure 7. Nominal-actual deviation analysis on the H1 hole.

It is worth noting that the proposed method offers a valuable advantage when compared to other methods presented in the literature. Specifically, the automatic optimizer for optimal scanning orientation can be tested with a manageable level of computational effort, as each step of the proposed model workflow is configurable (see Figure 2). In this study, calculation time ranged from a few hours since time was not considered a crucial factor, while the quality of the results was deemed a critical component.

5. Conclusions

In the presented work, a software tool to estimate the optimal CT scanning orientation is proposed, as well as the influence of scan orientation on CT image quality and CT measurement accuracy. A mathematical function (*score*) is proposed, which combines different statistical variables obtained from the projections of the parts and predicts the optimal orientation automatically. This tool can be defined as an automatic optimizer of the scanning orientation. The experimental results show the impact of sample orientation on the CT image quality, using CNR values as the metric, and how orientations predicted as the "worst" ones produce a great instability in the CT process by increasing the dispersion between measurement results (from 0.35% up to 2. 6%). In addition, the statistical variables are prioritized according to their influence on the CNR values (obtained experimentally), for different orientations on different parts. To the authors knowledge, this has not yet been documented in the literature. Thus, the result of the research presented in this article can be of interest to the industrial CT community, as there is currently a paucity of correlations with experimental CT data in the literature and the use of simulation data remains predominant. In future research a proper metrological frame will be made, adjusting the scale factor, and including a higher number of repetitions an orientations in the process. Additionally, different part geometries will be included to translate these relationships to different boundary conditions. Moreover, to enable scans of the samples at different angular tilt positions (α and β) from the CT rotation axis, an instrument shall be introduced in the workflow that allows to adjust the angles on the rotary table accurately. To further improve the tool's industrial applicability, optimization of its calculation time will be addressed.

Acknowledgements

Grant PID2020-118478RB-100 funded by MCIN/AEI/10.13039/ 501100011033. Grant KK-2022/00030 funded by Department of the Basque Government's Ministry of Economic Development, Sustainability and the Environment.

References

[1] Jiménez-Pacheco R, Ontiveros S, Yagüe-Fabra JA, Zanini F, et al. Assessment of Gradient-Based Algorithm for Surface Determination in Multi-Material Gap Measurements by X ray Computed Tomography. Materials 2020;13:5650.

[2] Villarraga-Gómez H, Herazo EL, Smith ST. X-ray computed tomography: from medical imaging to dimensional metrology. Precis Eng 2019;60:544–69.

[3] Villarraga-Gómez H, Amirkhanov A, Heinzl C, Smith ST. Assessing the effect of sample orientation on dimensional X-ray computed tomography through experimental and simulated data. Measurement 2021;178:109343.

[4] Butzhammer L, Müller AM, Hausotte T. Comparison of geometrically derived quality criteria regarding optimal workpiece orientation for computed tomography measurements. 10th Conf Ind. Comput. Tomogr. ICT 2020Wels Austria, 2020.

[5] Bellon C, Jaenisch G-R. aRTist–analytical RT inspection simulation tool. Proc DIR, 2007, p. 25–7.

[6] Ito T, Ohtake Y, Suzuki H. Orientation optimization and jig construction for X-ray CT scanning. 10th Conf. Ind. Comput. Tomogr., vol. 1, 2020, p. 1–9.

[7] Holgado I, Iglesias J, Ortega N, Plaza S, Pascual A. CT image quality influence on different material Edge Response Functions for accurate metrological applications. IOP Conf. Ser. Mater. Sci. Eng., vol. 1193, IOP Publishing; 2021, p. 012064.

[8] Arenhart FA, Nardelli VC, Donatelli GD. Comparison of surface-based and image-based quality metrics for the analysis of dimensional computed tomography data. Case Stud Nondestruct Test Eval 2016;6:111–21.

[9] Taylor CJ, Kriegman DJ. Minimization on the Lie group SO (3) and related manifolds 1994.