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Article

Method for Determining the Influence of Material Density on Set Parameters in X-ray Computed Tomography Measurement

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Abstract: The CT (computed tomography) scanner has been used for many years now not only for medical measurements, but also in many industries, mostly for tasks such as defectoscopy, measuring sheet thickness, checking the joining of materials, but also for measuring the geometry of individual components. It is a good complement to coordinate contact and non-contact measurements for intra-structural measurements and inaccessible places. The variety of materials, however, makes it very difficult to select individual CT parameters. In this paper, a curve for selecting the maximum and minimum voltage of the lamp depending on the density of a given material has been determined and an interpolation polynomial (1d third-degree polynomial) has been used, by defining 3rd-degree glued functions (cubic spline) to determine intermediate voltage values to a given material density, so as to determine full data ranges. This approach will facilitate the work of selecting scanning parameters for nondestructive testing, as this is a difficult process and sometimes consumes half of the measurement time. Work is underway at the Accredited Coordinate Metrology Laboratory to develop a multi-criteria matrix for selecting CT measurement parameters for measurement accuracy.

Keywords: X-ray computed tomography; material density; measurement accuracy; coordinate measurement; linear radiation absorption coefficient

1. Introduction

Industrial measurement using a computed tomography (CT) system is an advanced technique that uses X-rays to scan an object and create a three-dimensional reconstruction of it. It is a technology widely used in industry, especially in quality control and materials analysis. The design of such a system is slightly different from a medical measurement system, but the principle of measurement remains the same. Such measurement is used for precise geometric measurements, internal defect analysis, quality control, reverse engineering or testing of materials and composite components [1–5].

Although CT has long been used for medical measurements it is only since about 2005 that it has found its way into geometry measurement [1–3]. Unfortunately, for the measurement of industrial components, where it is required to be able to measure parts made with an accuracy of 5–9 class, setting the appropriate parameters of CT, is difficult and has a lot of parameters that can significantly

change the process. The figure below (Figure 1) shows the influences on the accuracy of the measurement so obtained [1].

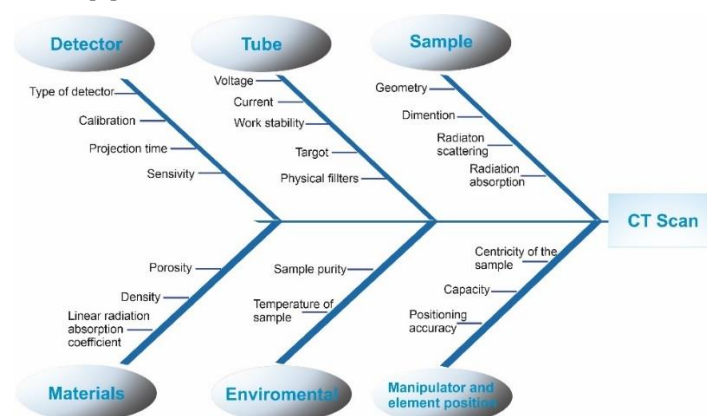


Figure 1. Elements affecting the accuracy of the measurement of the CT performed [4].

As you can see there are a lot of factors that define measurement. The first problem, which is still not fully resolved and divides the user and manufacturer community, is the calibration and sometimes the adjustment of these devices. Manufacturers have developed standards that adjust the machine within a small range of the measurement space, which users disagree with, repeatedly proving that the position of the measuring element in different parts of the space is crucial. This is at least related to the resolution of the system [6–10]. Another important aspect on which research was conducted was the analysis of the impact of algorithms for assembling 2D images into a 3D object. In medical research, it has been found that a reconstructive iterative algorithm improves qualitative analysis, as the amount of noise increases with decreasing thickness and cross-sections [11].

Subsequent research has been conducted on CT artifact reduction methods, which also introduce ambiguity in the results. In [12], a new method was proposed to reduce CT artifacts by using multiple X-ray CT scanning, in which CT data fusion is combined with optimized selection of scan angle combinations. In [13], a projection sinogram-based artifact correction method was proposed. The proposed method calibrates geometric deviations in an industrial computed tomography (CT) system with parallel angles and effectively eliminates geometric artifacts in reconstructed CT images. In [14], a modification of a single-grid phase contrast X-ray imaging (PCXI) system was proposed using a Fourier domain analysis technique to extract absorption, scattering and differential phase contrast images. The proposed modification involves rotating the X-ray grating on the image plane to achieve spectral separation between the desired information and moiré artifact, which is introduced by superposition of the periodic grating shadow image and periodic sampling by the detector. This optimization was intended to increase the spectral separation between the fundamental spectrum (lower frequency) and the spectral harmonics (higher frequency) used to extract different image contrasts.

An extension of the research presented above is the work on the introduction of virtual optimization solutions to reduce time or improve measurement accuracy [15,16]. In [17], meanwhile, the impact of spectrum pre-filtering and beam hardening correction on internal and external dimensional measurements is evaluated using a proven simulation tool. In [18], it is described what industrial users find difficult in evaluating the uncertainty of CT measurements and the metrological performance of CT systems. This paper examines the state of the art in industrial CT metrology, with a focus on accuracy and traceability issues, by examining specific results obtained from the first international comparison of CT systems for dimensional metrology. The comparison included 15 CT systems operated by experts in Europe, America and Asia.

As presented above, CT used for industrial measurements is still not fully recognized. When working with CT, a major problem is the selection of scanning parameters [19,20]. There are some input data on which to base the type of plot of the maximum voltage set on the CT lamp against the thickness of several basic materials like Cu, Fe, Ti or Al. (Figure 2).

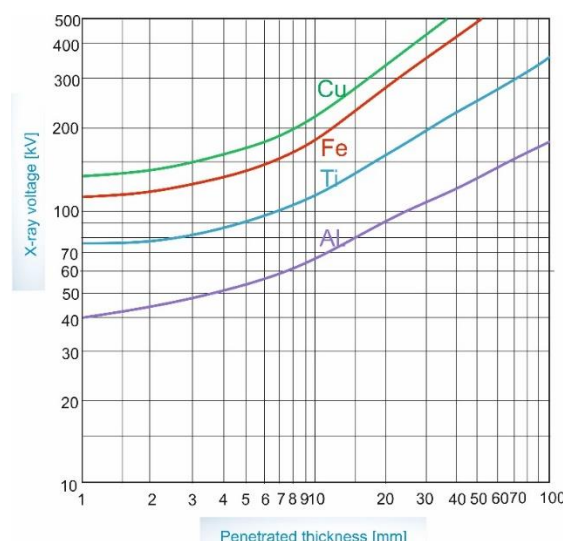


Figure 2. Relationship between the selected voltage and material thickness [16].

However, this is not a sufficient basis, especially if CT is used in small batch production, where we have constant changes of products as well as their materials. Searching constantly for new parameters for each job causes too much downtime, which companies cannot afford [21,22]. Therefore, in this article, samples were designed with a known density that increased logarithmically. Initially, one material was used, where the density of the material was increased by compression. Unfortunately, the resulting parameters had too small a variation (from 6.139 to 7.037 g/m³) for noticeable differences to be observed in the choice of scanning parameters, screening the material. Samples with a large amplitude of variation in material density (from 0.661 to 8.429 g/m³) were then made. Because the same material in terms of atomic composition can have different densities (e.g., liquid and vapor water) [23–25]. For the measurement, the manufacturer's settings were used, at which he performs device adjustment. During the tests, samples of the same volume and dimensions were used, but with increasing density and, consequently, mass. A plot of the minimum and maximum voltage set on the tomography lamp against the density of the material was determined. Polynomial interpolation (1d third-degree polynomial) was used, by defining 3rd-degree glued functions (cubic spline) to determine intermediate voltage values up to a given material density, so as to determine full data ranges. Each sample's dimensions were measured on a Coordinate Measuring Machine at the Accredited Coordinate Metrology Laboratory of the Cracow University of Technology.

2. Measuring Geometry with CT

The X-ray computed tomography provides imaging based on X-rays of the object under examination. The radiation beam as it passes through the object is attenuated, a process that depends on the thickness of the absorbing material, the absorption coefficient referenced, or the density of the material to the same length units. During the measurement process, hundreds or thousands of 2D X-ray images are usually taken for different angular positions of the lamp-detector system relative to the object being measured. As a result of the reconstruction from the 2D shots, a 3D spatial image is obtained (Figure 3).

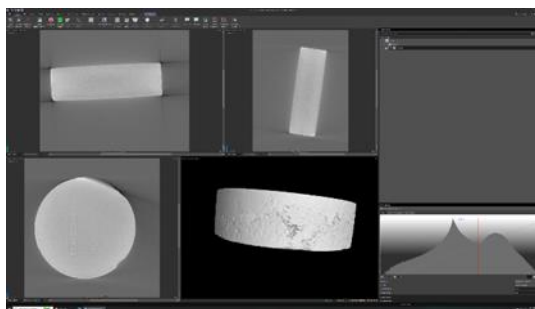


Figure 3. Reconstruction view of measurement samples measured with CT.

The X-ray tomography is classified as a non-destructive test. X-rays are characterized by their ability to penetrate bodies that are in different states of aggregation, and when they pass through a material they are weakened. This relationship can be described by a linear absorption coefficient, where a given medium of a certain thickness transmits the same fraction of the number of photons, and their number is (1).

$$N_x = N_0 e^{-\mu g} \quad (1)$$

where: N_x – number of photons after passing through the medium, N_0 – number of incident photons, μ – linear absorption coefficient of radiation, g – thickness of the sample.

The intensity of X-rays depends on the number of photons – Eq. (1), and this can also be described by the dependence of the intensity of radiation after passing through the object (I_x) in relation to its initial value (I_0), as follow

$$I_x = I_0 e^{-\mu g} \quad (2)$$

where: I_x – intensity of radiation after passing through the medium, I_0 – initial value of radiation intensity, μ – linear absorption coefficient of radiation.

As can be seen from Eq. (2), the permeability depends on factors such as the thickness of the absorbing material (g) and the absorption coefficient (μ) related to the same units of length. The linear absorption coefficient of radiation depends on the wavelength and atomic number of the material being permeated (3):

$$\mu = k \lambda^3 Z^3 \quad (3)$$

where: μ – linear absorption coefficient of radiation, k – proportionality factor, λ – wavelength of radiation, Z – atomic number of the material of the medium being scanned.

An increase in the atomic number of the material of the medium weakens the penetrability of X-rays. The linear absorption coefficient can be replaced by the mass coefficient, which expresses the probability of interaction of radiation with a unit mass of material, is given by

$$\mu_m = \mu / \rho \quad (4)$$

where: μ_m – mass absorption coefficient, μ – linear radiation absorption coefficient, ρ – material density of the medium.

2. Test Conducting

In order to determine, the selection of setting parameters depending on the density of the material, 15 samples with densities ranging from 0.661 g/cm³ to 8.429 g/cm³ were measured, where the last value did not give positive results, the measurements could not be made without changing the rest of the device settings (Table 1).

Table 1. Samples parametres.

Sample number	Density D [g/cm ³]	Mass m [g]	Size V [cm ³]	High h [mm]	Diameter d [mm]
C	0.661	2.472	3.739	7.956	24.463
G	1.126	3.448	3.061	8.030	22.031
F	1.136	3.548	3.123	7.887	22.455
D	1.266	4.549	3.592	7.900	24.061
A	2.785	8.718	3.130	7.877	22.493
10	5.749	17.838	3.103	6.071	25.510
11	5.934	18.448	3.109	6.078	25.520
12	6.139	19.147	3.119	6.064	25.591
13	6.392	19.928	3.117	6.079	25.553
14	6.551	20.310	3.100	6.050	25.543
15	6.638	20.627	3.107	6.061	25.549
16	6.866	21.239	3.093	6.043	25.530
17	6.957	21.330	3.066	5.987	25.535
B	7.632	23.289	3.052	8.019	22.012
E	8.429	27.407	3.252	7.779	23.070

Cylindrical samples of the tested materials were prepared on a TOP-300 universal lathe. Density tests were performed on a Pycnomatic ATC helium pycnometer from Thermo Scientific according to the ASTM D792, ISO 1183 standard. One of three measuring containers with a volume of 40 cm³ was used, measurement temperature 25 °C, gas pressure stability 0.001 kPa. Calibration method using certified stainless steel balls. Repeatability and accuracy modes at the level of 0.01 % were maintained. Density measurement accuracy 0.001 g/cm³. Helium 6.0 was used for the tests. Due to the quality of CT scans, the histogram should be in the range of 200–10000.

The tests were performed on a Waygate Technologies Phoenix V|tome|x M Metrology Edition CT scanner with an accuracy of (3.8 + L/100 [mm]) μm, using a Microtube X-ray tube with a maximum power of 240 W with a measurement resolution of less than 1 μm. In addition, a Nanotube X-ray tube with a measurement resolution of 0.2 μm is installed in an industrial CT scanner located at the Coordinate Metrology Laboratory of the Faculty of Mechanical Engineering at the Cracow University of Technology. The 3D scanning measurement space is 420 × 400 mm.

Figure 4 shows the CT scanner and microtube.



Figure 4. CT scanner and microtube.

The maximum weight of the sample can be as much as 50 kg. Table 2 includes the operating parameters of the tomography.

Table 2. Operating parameters of the tomography.

Parameters	Value
Sensitivity	1
Binning	1×1
Current	300 μA
Voltage	70–220 kV
Timing	100 ms

Voltage is responsible for the force with which photons fly through the material, and current is responsible for the photon flux density. Binning is responsible for combining pixels. Sensitivity affects the sensitivity of the detector by either enhancing or reducing it. This option is responsible for amplifying the signal and detecting small changes, but can lead to more artifacts. Timing is responsible for the detector's exposure time to incoming radiation. The current value was as per the calibration of the device.

Each sample was placed in the CT space at the exact distance at which the manufacturer recommends performing the adjustment. This is very important, as the resolution of the measurement depends on the distance of the measuring element from the X-ray tube. Voltage adjustments, both minimum and maximum, were selected for each part. In this task, it should be noted that the device will indicate if the parameters are too high, showing an alarm about the possibility of damage to the device. The lower limit, on the other hand, is determined by checking the histogram readings and selecting them according to the manufacturer's assumptions and based on the laws of physics.

The samples were measured according to the selected parameters, and their geometric parameters were then compared to the nominals mapped on the CMM. From the results, a tube voltage range selection curve was determined for the given material densities. To show the errors when measuring with inappropriate parameters, the differences are shown in Figure 5.

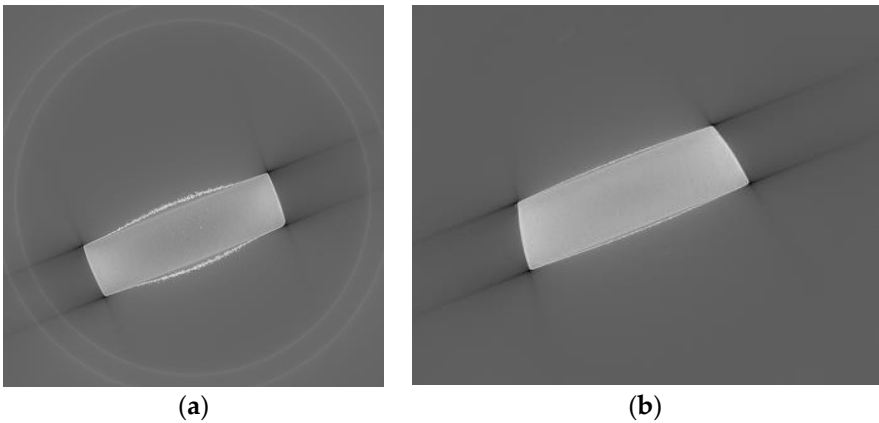


Figure 5. Scan a sample with a bad (a) and good (b) histogram.

Figure 5 (a) shows ring artifacts that were created during scanning. This is caused by improper tomography operating parameters, which caused the histogram not to be in the range of 200–10000. On the other hand, in Figure 5 (b) there are no ring artifacts, because the scanning parameters were properly selected and the histogram was in the range of 200–10000. Results of selected – sample 11. In the case of the scan from Figure 5 (a), the distance between the upper and lower planes is 6.392 mm, and in the case of the sample from Figure 5 (b), the distance between the lower and upper planes is 6.226 mm. Height determined on the Zeiss Eclipse coordinate measuring machine 6.192 mm.

In all measurements, the more accurate results were from the appropriate range of the histogram, the maximum difference is $6.2 \mu\text{m}$.

In order to make the results complete, interpolations (1d with third-degree polynomials) were used to feed into the matrix for selecting the setting parameters from the material density, by defining 3rd-degree glued functions (cubic spline) also called (jargon-wise) splines. The spline method uses functions defined as low-degree polynomials separately for each segment between adjacent interpolation nodes. The presented local polynomials are selected in such a way that, in addition to the interpolation conditions, they satisfy the gluing conditions so that the whole spline is a function with sufficient regularity. In this case, there were 5 interpolation nodes ($n + 1$) with coordinates $(x_0, y_0), (x_1, y_1), \dots, (x_n, y_n)$, where: x – material density, y – tension. It was necessary to find n polynomials of the third degree with equations connecting the points $(x_i - 1, y_i - 1)$, where $i = 1, 2, \dots, n$, so that the line connecting them was smooth. So it was necessary to determine the values of $4n$ coefficients a_i, b_i, c_i and d_i for $i = 1, 2, \dots, n$, as follow

$$f_i(x) = a_i + b_i x + c_i x^2 + d_i x^3 \quad (5)$$

For the task to be calculated correctly, certain conditions had to be formulated:

– using the assumption of continuity of the line was assumed

$$f_i(x_i) = y_i, \quad f_{i+1}(x_i) = y_i, \quad \text{for } i = 1, 2, \dots, n - 1 \quad (6)$$

– the first polynomial should pass through the initial point (x_0, y_0) , while the last polynomial should pass through the final point (x_n, y_n) , hence:

$$f_1(x_0) = y_0, \quad f_n(x_n) = y_n, \quad \text{for } i = 1, 2, \dots, n - 1 \quad (7)$$

– it was also assumed that there is a condition at the interpolation nodes

$$f''_i(x_i) = f''_{i-1}(x_i) \quad (8)$$

where $i = 1, 2, \dots, n - 1$.

– received

$$2c_i + 6d_i x_i = 2c_{i+1} + 6d_{i+1} x_i \quad (9)$$

From condition given by Eq. (7), $2n - 2$ equations are obtained, from conditions given by Eqs. (8) and (9), $n - 1$ equations each, finally making $4n - 2$ equations. Two more equations are missing to solve the task. Therefore, in addition, to obtain splines with linear ends, it was assumed that:

$$f''_1(x_0) = 0 \quad (10)$$

what gives $2c_1 + 6d_1 x_0 = 0$,
and

$$f''_n(x_n) = 0 \quad (11)$$

what gives $2c_n + 6d_n x_n = 0$,

while to obtain splines with parabolic ends was additionally adopted:

$$f''_n(x_n) = f''_n(x_{n-1}) \quad (12)$$

what gives $2c_n + 6d_n x_n = 2c_n + 6d_n x_{n-1}$.

Finally, linearly extrapolate the second derivative for the ends of the interval given by the following formulae

$$\frac{f''_1(x_1) - f''_1(x_0)}{x_1 - x_0} = \frac{f''_2(x_2) - f''_2(x_1)}{x_2 - x_1} \quad (13)$$

and

$$\frac{f''_n(x_n) - f''_n(x_{n-1})}{x_n - x_{n-1}} = \frac{f''_{n-1}(x_{n-1}) - f''_{n-1}(x_{n-2})}{x_{n-1} - x_{n-2}} \quad (14)$$

to get in splines with the ends of the third degree.
Figure 6 shows the curve of selection of the voltage in relation to the material density.

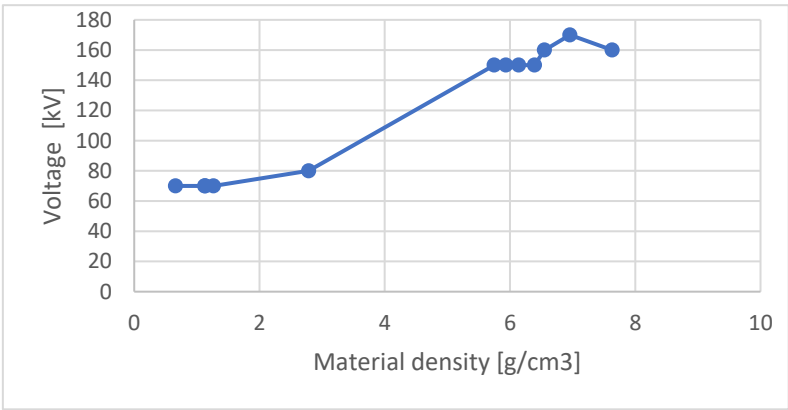


Figure 6. Curve of selection of the voltage in relations to material density.

Figure 7 shows the interpolation of the minimum lamp intensity adjusted to the material density.

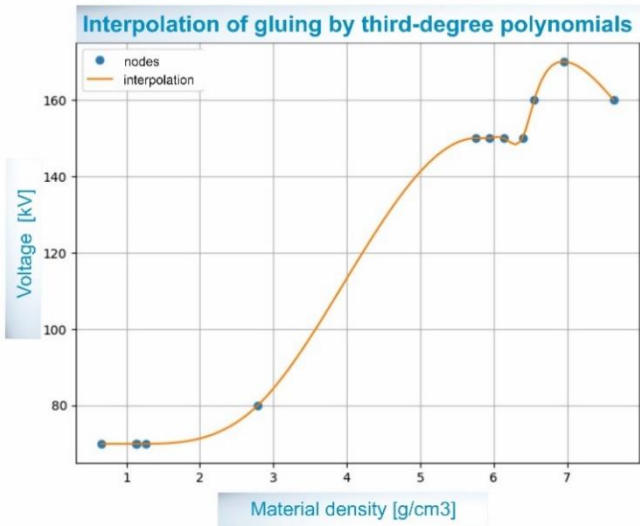


Figure 7. Interpolation of the minimum lamp intensity adjusted to the material density.

Table 3. Results for 50 interpolation step.

Material density [g/cm3]	Voltage [kV]	Material density [g/cm3]	Voltage [kV]	Material density [g/cm3]	Voltage [kV]	Material density [g/cm3]	Voltage [kV]	Material density [g/cm3]	Voltage [kV]
0.661	70	2.083	72	3.506	98	4.929	140	6.352	149
0.803	70	2.226	73	3.649	102	5.071	143	6.494	156
0.945	70	2.368	74	3.791	107	5.213	145	6.636	165
1.087	70	2.510	76	3.933	111	5.356	147	6.778	169
1.230	70	2.653	78	4.075	116	5.498	149	6.921	170
1.372	70	2.795	80	4.218	120	5.641	150	7.063	169
1.514	70	2.937	83	4.360	125	5.782	150	7.205	168
1.657	70	3.079	86	4.502	129	5.925	150	7.347	166
1.799	70	3.222	90	4.644	133	6.067	150	7.490	163
1.941	71	3.364	94	4.787	136	6.209	149	7.632	160

3. Conclusions

In this study, the influence of material densities on the selection of appropriate lamp parameters for CT measurement can be observed. A minimum voltage selection curve was determined for given material densities. The results ranged from 70 to 160 kV for densities from 0.661 to 7.632 g/m³. The maximum voltage remained at one level, i.e. 190 kV. In order to make the results complete, interpolations (1d with third-degree polynomials) were used to feed into the matrix for the selection of setting parameters from the material density, by determining the 3rd-degree glued functions (cubic spline). Fifty tension values were generated, averaging every 0.200 g/m³ (Table 3 and Figure 7).

Work on the development of a multi-criteria matrix for the selection of CT measurement parameters in relation to the physical properties of materials is being carried out at the Accredited Coordinate Metrology Laboratory of the Cracow University of Technology. One of the parameters influencing the accuracy of the obtained measurement, as well as the appropriate selection of parameters for CT measurement, is precisely the material density. In further work, analogous to the present study, curves will also be determined for the given material densities, but with increasing thicknesses of the materials in question, as well as many other factors influencing the result of a CT measurement.

A major challenge when it comes to the use of the computed tomography for metrology tasks is the measurement of components consisting of a minimum of two materials, i.e. electronic components, automotive components, e.g. an entire lamp that additionally has a painted coating. This is a very problematic task, because when processing the results, the algorithm does not quite cope with the distinction between materials. Therefore, further work will be carried out, which will also aim to make the ISO 50 algorithm, responsible for determining the boundary between one material and the other, dependent on parameters such as material density.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bartkowiak, T.; Gapiński, B.; Wieczorowski, M.; Mietliński, P. and Brown, C.A. Capturing and characterizing geometric complexities of metal additively manufactured parts using x-ray micro-computed tomography and multiscale curvature analyses. *Surf. Topogr. Metrol. Prop.* **2023**, 11/1, pp. 1–7, doi: [10.1088/2051-672X/acb3e7](https://doi.org/10.1088/2051-672X/acb3e7).
2. Thompson, A.; Maskery, I. and Leach, R.K. X-ray computed tomography for additive manufacturing: A review. *Meas. Sci. Technol.* **2016**, 27/7, pp. 1–25, doi: [10.1088/0957-0233/27/7/072001](https://doi.org/10.1088/0957-0233/27/7/072001).
3. Zanini, F.; Sbettega, E. and Carmignato, S. X-ray computed tomography for metal additive manufacturing: Challenges and solutions for accuracy enhancement. *Proc. CIRP.* **2018**, 75, pp. 114–118, doi: [10.1016/j.procir.2018.04.050](https://doi.org/10.1016/j.procir.2018.04.050).
4. Palczewska-Komsa, M.P.; Gapiński, B. and Nowicka, A. The influence of new bioactive materials on pulp–dentin complex regeneration in the assessment of cone bone computed tomography (CBCT) and computed micro-tomography (Micro-CT) from a present and future perspective. *J. Clin. Med.* **2022**, 11, pp. 1–27, doi: [10.3390/jcm11113091](https://doi.org/10.3390/jcm11113091).
5. Gapiński, B.; Wieczorowski, M.; Mietliński, P. and Mathia, T.G. Comparison of measurements realized on computed tomograph and optical Scanners for elements manufactured by wire arc additive manufacturing. *Lect. Notes Mech. Eng.* **2022**, pp. 127 – 141, 7th International Scientific-Technical Conference, doi: [10.1007/978-3-031-03925-6_12](https://doi.org/10.1007/978-3-031-03925-6_12).
6. De Chiffre, L.; Carmignato, S. ; Kruth, J.P; Schmitt, R. and Weckenmann, A. Industrial application of computed tomography. *CIRP Ann. Manuf. Techn.* **2014**, 63, pp. 655–677, doi: [10.1016/j.cirp.2014.05.011](https://doi.org/10.1016/j.cirp.2014.05.011).
7. Villarraga Gómez, H.; Herazo, E.L. and Smith, S.T. X-ray computed tomography: from medical imaging to dimensional metrology. *Precis. Eng.* **2019**, 60, pp. 544–569, doi: [10.1016/j.precisioneng.2019.06.007](https://doi.org/10.1016/j.precisioneng.2019.06.007).

8. Laquai, R.; Illema, J.; Bartscher, M. and Neuschaefer-Rube, U. The metrological structural resolution for dimensional x-ray CT: analysis of the comparability between the CEB and the PBS method. *Meas. Sci. Technol.* **2023**, 34/8, pp. 1–10, doi: [10.1088/1361-6501/accd8b](https://doi.org/10.1088/1361-6501/accd8b).
9. Reiter, M.; de Oliveira, F.B.; Bartscher, M.; Gusenbauer, Ch. and Kastner, J. Case study of empirical beam hardening correction methods for dimensional X-ray computed tomography using a dedicated multi-material reference standard. *J. Nondestruct. Eval.* **2019**, 38/10, pp. 1–15, doi: [10.1007/s10921-018-0548-3](https://doi.org/10.1007/s10921-018-0548-3).
10. Kiekens, K.; Welkenhuyzen, F.; Tan, Y.; Bleys, P.; Voet, A.; Dewulf, W. and Kruth, J.P. A test object for calibration and accuracy assessment in X-ray CT metrology. *Meas. Sci. Technol.* **2011**, 22/11, pp. 1–12, doi: [10.1088/0957-0233/22/11/115502](https://doi.org/10.1088/0957-0233/22/11/115502).
11. Fareed, A.; Andrea, M.D.; Vavere, L.; Mpha, M.S.; Zimmermann, E.; Tanami, Y.; Steveson, Ch.; Matheson, M.; Narinder P.; Clouse, M.; Cox, Ch.; Lima, J.A.C. and Arbab-Zadeh, A. Impact of iterative reconstruction vs. filtered back projection on image quality in 320-slice CT coronary angiography Insights from the CORE320 multicenter study. *J. Med.* **2017**, 96/48, pp. 1–10, doi: [10.1097/MD.00000000000008452](https://doi.org/10.1097/MD.00000000000008452).
12. Tan, Y.; Ohtak, Y. and Suzuki, H. Scan angle selection and volume fusion for reducing metal artifacts by multiple X-ray CT scanning. *Precis. Eng.* **2022**, 74, pp. 384–395, doi: [10.1016/j.precisioneng.2021.07.020](https://doi.org/10.1016/j.precisioneng.2021.07.020).
13. Xu, S.; Sheng, J.; Li, Z.; Long, Ch.; Jiang, Y.; Tan, H. and Duan, L. Geometric artifacts correction of equiangular fan-beam industrial CT system. *NDT and E. International.* **2024**, p. 103197, doi: [10.1016/j.ndteint.2024.103197](https://doi.org/10.1016/j.ndteint.2024.103197).
14. Lee, H.W.; Lim, H.W.; Jeon, D.H.; Park, C.K.; Lee, D.Y.; Cho, H.S.; Seo, C.W.; Kim, K.S.; Kim, G.A.; Park, S.Y.; Kang, S.Y.; Park, J.E.; Kim, W.S.; Lim, Y.H. and Woo, T.H. Eliminating artifacts in single-grid phase-contrast x-ray imaging for improving image quality. *Comput. Biol. Med.* **2018**, 97, pp. 74–82, doi: [10.1364/josa.72.001238](https://doi.org/10.1364/josa.72.001238).
15. Reiter, M.; Harrer, B.; Heinzl, Ch.; Salaberger, D.; Gusenbauer, Ch.; Kuhn, Ch. and Kastner, J. Simulation Aided Study for Optimising Industrial X-ray CT Scan Parameters for non-destructive testing and materials characterisation. *International Symposium on Digital Industrial Radiology and Computed Tomography – Poster 5.* **2010**, pp. 1–9, www.ndt.net/article/dir2011/papers/p5.pdf. (accessed: October 25, 2024).
16. Lin, Q.; Yang, M.; Meng, F.; Sun, L. and Tang, B. Calibration method of center of rotation under the displaced detector scanning for industrial CT. *Nucl. Instrum. Methods Phys. Res.* **2019**, 922 pp. 326–335, doi: [10.1016/j.nima.2018.11.131](https://doi.org/10.1016/j.nima.2018.11.131).
17. Liftona, J.J.; Malcolm, A.A. and McBride, J.W. A simulation-based study on the influence of beam hardening in X-ray computed tomography for dimensional metrology. *J. X-Ray Sci. Technol.* **2015**, 23/1, pp. 65–82, doi: [10.3233/XST-140471](https://doi.org/10.3233/XST-140471).
18. Carmignato, S. Accuracy of industrial computed tomography measurements: Experimental results from an international comparison. *CIRP Annal. Manuf. Techn.* **2012**, 61, pp. 491–494, doi: [10.1016/J.CIRP.2012.03.021](https://doi.org/10.1016/J.CIRP.2012.03.021).
19. Kubacki, R. “ITA- CT Basics”- ITA Poznan, **2023**, www.ita-polska.com.pl/wydarzenia/ct-scan-forum. (accessed: October 25, 2024).
20. Federico, P.; Huan, S.; Stefano, P. and Giovanni, M. A Surface determination technique for dimensional and geometrical analysis in industrial X-ray computed tomography. *Nanomanufacturing Metrol.* **2024**, 7, doi: [10.1007/s41871-024-00239-4](https://doi.org/10.1007/s41871-024-00239-4).
21. Yang, X.; Sun, W. and Giusca, C.L. An automated surface determination approach for computed tomography. *NDT and E. International.* **2022**, 13, doi: [10.1016/j.ndteint.2022.102697](https://doi.org/10.1016/j.ndteint.2022.102697).
22. Liu, W.; Chen, X.; Zeng, W.; Sun, W.; Gorman, D.; Wilson, A.; Qi, Q.; Scott, P.; Jiang, X. and Lou S. Comparison of X-ray computed tomography and coordinate-measuring system dimensional measurement for additive manufacturing parts using physical and simulation methods. *Measurement.* **2024**, 229, doi: [10.1016/j.measurement.2024.114414](https://doi.org/10.1016/j.measurement.2024.114414).
23. Yang, X.; Sun, W.; Giusca, C.L. Surface determination algorithm for accurate XCT bidirectional length measurements. *Precis. Eng.* **2024**, 85, pp. 40–47, doi: [10.1016/j.precisioneng.2023.09.003](https://doi.org/10.1016/j.precisioneng.2023.09.003).

24. Bellens, S.; Guerrero, P.; Vandewalle, P. and Dewulf, W. Machine learning in industrial X-ray computed tomography – a review. *CIRP J. Manuf. Sci. Technol.* **2024**, 51, pp. 324–341, doi: 10.1016/j.cirpj.2024.05.004.
25. Xu, B.; Ouidadi, H.; Van Handel, N. and Guo, S. Three-dimensional X-ray computed tomography image segmentation and point cloud reconstruction for internal defect identification in laser powder bed fused parts. *J. Manuf. Sci. Eng.* **2024**, 146/91, doi: 10.1115/1.4065179.

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