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Advanced Computed Tomography Techniques in the Field of Additive Manufacturing: Distortion Mitigation and Dimensional Measurements

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1 Background of the research

The rapid advancement of additive manufacturing (AM) technologies and hybrid structures presents significant challenges for dimensional metrology. For inspecting complex internal channels and hidden geometries, industrial X-ray computed tomography (XCT) has emerged as the primary non-destructive measurement tool [1, 2, 3]. However, the main obstacle to the metrological application of XCT lies in ensuring the traceability of measurement results and accurately quantifying measurement uncertainty [4, 5, 6].

Expanding the boundaries of tomographic measurement technology is also facilitated by the metrological investigation of neutron tomography (NCT). Neutron radiation possesses a unique capability to penetrate dense metals while remaining highly sensitive to some light elements [7, 8]. At the same time, the international literature has lacked a calibrated gauge and a methodology that would allow for a direct, objective comparison of the dimensional measurement capabilities of XCT and NCT systems.

The tomographic measurement of multi-material metal-polymer assemblies is similarly an under-explored area. Micro-scale air gaps forming at the contact interfaces of components, along with the significant density differences between materials, lead to image artifacts such as beam hardening and scattering, which systematically distort surface determination [9, 10]. To date, no comprehensive study in the literature has quantified the interactions between scanning parameters, air gap size, and image quality in the context of measurement errors [11, 12].

In the case of polymer parts manufactured by selective laser sintering (SLS), thermal distortions and shrinkage constitute the most significant quality issues. Although numerical simulations are widely used, a detailed metrological and statistical analysis of the effectiveness of measurement-based, corrective CAD compensation methods [13], as well as their systematic relationship with build chamber orientation, was still missing. The aim of this dissertation is to systematically explore and resolve these theoretical and practical shortcomings.

2 Objectives

The rise of AM and multi-material structures poses significant challenges to industrial metrology. While XCT has proven to be the most suitable method for precise and non-destructive measurement of complex internal geometries [14], several factors affecting measurement accuracy during its application remain fully unexplored. The aim of this research is to provide scientifically grounded answers to these challenges.

2.1 Shortcomings in the literature

An analysis of the relevant literature revealed several key shortcomings. Firstly, there is a lack of metrological comparison between tomographic systems, as no calibrated gauge or methodology previously existed to objectively compare the measurement performance of XCT and NCT systems while taking into account different material-radiation interactions [15, 16] and safe handling after neutron activation [17, 18]. Secondly, regarding the measurement of multi-material assemblies, the combined effect of image artifacts occurring at the interface of materials with different densities and the air gaps between components on dimensional measurement errors has not been systematically and quantitatively explored as a function of various scanning parameters [19, 20]. Thirdly, concerning the optimization of the accuracy of additive manufactured parts, a complex optimization procedure based on XCT measurements was missing, specifically one that simultaneously handles the geometric compensation of the CAD model and conscious positioning within the build space while also correcting the systematic calibration errors of the manufacturing equipment.

2.2 Research objectives

Based on these identified shortcomings, this research sets several primary objectives. The first goal is to develop and validate a new calibration phantom suitable for comparing XCT and NCT systems that provides adequate contrast for both methods while remaining safe for repeated use due to low post-neutron activation. The second objective is to identify the most appropriate uncertainty calculation method for comparing tomographic systems, determine the expanded measurement uncertainty of the neutron tomography system, and verify the metrological equivalence of neutron and X-ray tomography for specific measurement tasks. The third goal is to systematically investigate the effects of X-ray computed tomography scanning parameters, such as voxel size, pixel binning, exposure time, and rotation mode, on the contrast-to-noise ratio (CNR), signal-to-noise ratio (SNR), and measurement accuracy in single- and multi-material configurations. The fourth objective is to verify that multi-material arrangements and interfacial air gaps significantly increase measurement errors, particularly for lower-density polymers, thereby establishing a guideline for selecting optimal scanning parameters. The fifth and final objective is to investigate and characterize a process that combines XCT-based CAD model compensation with optimal build chamber orientation to minimize geometric deviations and systematic machine errors.

2.3 Research methodology

In order to achieve the objectives of this doctoral research, a systematic research framework built upon theoretical foundations and experimental validation was developed. The fundamental goal of this methodology is to investigate the industrial metrological limitations of computed tomography and the accuracy problems of additive manufacturing technologies in close correlation with each other, explored through three primary experimental pillars.

The first pillar of the research focused directly on the comparison of the dimensional metrology capabilities of XCT and NCT systems. A key element of this methodology was the design and fabrication of a novel, multi-material calibration phantom designed to provide adequate image contrast for both types of radiation. Following the measurements, measurement uncertainties were determined in accordance with international GUM guidelines, with a particular focus on the mathematical modeling of systematic measurement errors and the statistical verification of the metrological comparability of the systems.

The second pillar aimed to uncover the errors occurring during XCT measurements of multi-material metal-polymer components. The methodology was based on a full factorial design of experiments (DoE), during which scanning parameters were systematically varied. For these experiments, a custom hybrid specimen was designed, enabling the investigation of the effects of calibrated air gaps occurring at the interface of the metal and polymer. Significant sources of measurement errors were identified using reference measurements and multi-factor analysis of variance.

The third pillar targeted the reduction of thermomechanical distortions in thin-walled polyamide parts produced by selective laser sintering. The investigated methodology consisted of an iterative, closed-loop correction process based on the XCT measurement of parts from the first manufacturing cycle. The initial CAD model was modified using the inverse of the displacement vectors calculated from the measured deviations through Non-Uniform Rational B-Splines surface compensation, and then the improvement in the geometric accuracy of the remanufactured parts as well as the effect of build-space orientation were verified using statistical tests.

3 Investigation methods

3.1 Metrological comparison of X-ray and neutron tomography

The metrological comparison of XCT and NCT systems, along with the determination of measurement uncertainties, requires a complex methodology. The experimental process spans from the design and fabrication of the multi-material calibration phantom, through physical measurements, to uncertainty determination according to international metrological guidelines and statistical evaluation.

The calibration phantom was designed in accordance with the specifications of the relevant metrological guideline. To ensure geometric asymmetry, the spheres were aligned in a straight line, and the center sphere was nominally offset from the symmetry plane, allowing to measure several different length values. Due to the differing physical interactions of X-ray and neutron radiation, zirconium dioxide was selected as the material for the spheres, providing adequate contrast for both methods. The support structure was made of Ti6Al4V titanium alloy to avoid neutron activation, and assembly was achieved using purely mechanical fastening with clamping plates equipped with conical cavities, instead of adhesive or solder.

Prior to physical measurements, the precise geometric dimensions of the phantom were determined using a high-precision tactile coordinate measuring machine, the averaged results of which were considered the reference values. During the tomographic scannings, three different categories of XCT system were used to reveal system-level differences. Neutron tomography measurements were performed at the RAD imaging station of the Budapest Neutron Centre's research reactor, where the thermal neutron beam was optimized using a sapphire filter.

From the captured projection images, 3D voxel volumes were reconstructed using reconstruction software, and spheres were fitted to the surface points in VGStudio Max software using the least squares method (Gauss) to determine distances. To quantify measurement uncertainty, a mathematical model of the measurement was formulated, taking into account input factors such as the value indicated by the device, reference measurement corrections, repeatability standard deviation, surface inhomogeneity, thermal expansion, and measurement bias.

To address systematic measurement error, four different mathematical methods were used to incorporate bias into the uncertainty calculation, including root-sum-square methods, conservative linear addition, and integration as random variable according to the VDA 5 automotive recommendation. The metrological comparability of the different tomographic devices was analysed by calculating normalised error values, where an absolute value of less than one indicated the metrological equivalence of the measurement results.

3.2 Investigation of Dimensional Measurements Using X-ray Tomography for Multi-Material Parts

Coordinate X-ray tomography of hybrid parts assembled from metal and plastic faces severe physical and metrological limitations. To explore these obstacles and quantify measurement errors, a multifaceted experimental and statistical methodology was developed to analyze the phenomena occurring at the interface of AlMgSi1 aluminum alloy and polyoxymethylene.

The experimental work began with the CNC machining of the specimen. On the outer surface of the polyoxymethylene pins, which fit into holes machined into the aluminum body, seven stepped segments were formed. By progressively reducing their diameters, precisely controlled air gaps ranging from 0 to 125 micrometers were created between the metal and plastic surfaces in the assembled specimen. Measurements were performed in three configurations, scanning the aluminum body and plastic pins separately for single-material cases, and scanning them in their assembled state for the multi-material investigation.

To establish a reliable baseline, the reference dimensions of all holes and pin segments were determined using a high-precision tactile coordinate measuring machine before the tomographic scans. The X-ray tomography scans were performed using a metrological coordinate XCT system according to a full three-factor experimental design run at two levels, where the investigated factors were the combination of detector pixel binning and exposure time, the window width determining the voxel size, and continuous versus intermittent rotation modes.

Segmentation of the reconstructed 3D voxel volumes was performed in Winwerth. While automatic surface determination yielded adequate results for single-material scans, a local search window segmentation was applied to the multi-material hybrid volumes due to the massive density difference between metal and plastic. During dimensional evaluation, cross-sections were made on the point clouds at heights corresponding to the reference measurements, and tomographic diameter values were determined by fitting Gaussian circles to the extracted points.

To explore the relationship between physical measurement accuracy and image quality, local signal-to-noise ratio and contrast-to-noise ratio analyses were performed using ring-shaped volumetric regions fitted to the centerlines of the pin segments. Finally, a four-factor analysis of variance was applied at a 95% significance level to identify significant sources of measurement error and quantify interactions between parameters.

3.3 Investigation of SLS technology using XCT

During selective laser sintering, thin-walled polymer parts are highly prone to distortion due to thermomechanical processes occurring during the building and cooling phases. To systematically reduce these geometric deviations and increase manufacturing accuracy, an iterative CAD model compensation method based on X-ray computed tomography measurements was developed.

For the experiment, a thin-walled specimen containing both flat and cylindrical surfaces was designed specifically to induce and measure thermally driven distortions. For manufacturing, industrial-grade polyamide-12 powder was used, 3D printed in a ProX SLS 6100 machine. To investigate the influence of local thermomechanical effects and orientation within the build volume, the specimens were placed in five different spatial orientations in the build chamber, positioning ten parts per orientation.

Following printing and post-processing, measuement of the specimens were performed using an XCT system. After automatic surface determination on the reconstructed voxel volumes, a robust coordinate metrology program was executed in VGStudio Max. The coordinate system for the measurements was established using the 3-2-1 method, followed by the determination of plane-to-plane distances, as well as the diameters and positions of the cylindrical surfaces.

After quantifying the distortions, the surface point clouds were aligned with the nominal 3D models, and the initial model was deformed using the inverse of the displacement vectors through Non-Uniform Rational B-Splines to generate compensated models. These models were exported, and a second manufacturing run was executed under identical parameters, after which the new specimens printed from the compensated models were remeasured in the XCT system.

To verify the effectiveness of the compensation, nominal deviations from both cycles were subjected to statistical analysis. The variance of the distances between flat surfaces was analyzed using Levene's test, proving that the deviation variance significantly decreased as a result of the compensation. Calibration errors of the manufacturing machine's coordinate axes were revealed using multi-factor analysis of variance, which confirmed the elimination of systematic directional dependence, while the Kruskal-Wallis test of the position errors of cylindrical surfaces demonstrated the beneficial effect of optimal spatial orientation.

4 New scientific results

1. Thesis: I have developed and validated a methodology [S1] and a novel calibration phantom suitable for the objective metrological comparison of X-ray (XCT) and neutron tomography (NCT) systems, the material structure criteria of which I determined in such a way that they provide adequate contrast for both imaging methods [S2], while the low post-neutron radiation activity and short half-life allow for the safe and repeated use of the gauge [S2]. I successfully validated the model using yttria-stabilized zirconia spheres and a Ti6Al4V titanium alloy support structure.

2. Thesis: I have demonstrated that due to the significant systematic error (bias) of tomographic measurements, the uncertainty calculation method according to the VDA 5 recommendation provides the most reliable result when comparing different systems [S1]. Applying this model, I determined the expanded measurement uncertainty of the neutron tomography system of the Budapest Neutron Centre (0.092 mm, k=2), and verified that in the case of distance

measurement between flat surfaces, neutron and metrology-grade X-ray tomography yield metrologically comparable results ($|E_N| \leq 1$) [S1]. Although the significantly larger uncertainty of NCT results in a wider acceptance range, the E_N values prove that the deviations between the two methods remain within this limit of error, meaning that NCT measurements are free from significant systematic error.

3. Thesis: I have quantitatively proven that during multi-material (metal-polymer) XCT measurements, the size of the air gap between the components and the density difference exert a complex, significant effect on the measurement accuracy. The theoretical basis of this relationship is that the image artifacts occurring at high-density-difference interfaces locally distort the threshold calculation of surface determination algorithms, which effect results in a non-linear measurement error as the air gap increases [S3].

a. I proved that a significant difference in measurement accuracy exists between single-material and multi-material measurement configurations. For multi-material test specimens, the measurement error can increase up to eightfold, which is particularly significant for POM components (rising from 11 μm to 50 μm in the best-case scenario), while it is more moderate for aluminum components (from 6 μm to 20 μm) [S3].

b. I determined that for multi-material test specimens, the size of the air gaps plays a decisive role in the development of measurement accuracy. Reducing the voxel size (to 68 μm) and applying the optimized exposure parameters (1x1 binning, 250 ms exposure time) significantly reduces the measurement error, especially at material boundaries containing air gaps [190]. The measurement error systematically increases with the growth of air gaps (from 25 μm to 125 μm), and then decreases at segments without air gaps [S3].

c. I demonstrated that in the multi-material configuration, the presence of the higher-density material (aluminum) causes significant surface artifacts during the measurement of the lower-density material (POM), which provides a valuable guide for optimizing XCT scanning parameters in industrial metrological applications [S3, S4].

4. Thesis: I have shown that the relationship between XCT scanning parameters (voxel size, pixel binning) and image quality indicators (CNR, SNR) fundamentally differs for single- and multi-material measurements: while in a single-material configuration, the smaller voxel size clearly improves accuracy, in the multi-material case, the effect of the parameters follows complex patterns, where the signal-to-noise ratio (SNR) and grey value of the air gap between the components also show characteristic, setting-dependent changes [S4].

a. For single-material test specimens, I verified that smaller voxel sizes (68 μm) consistently result in higher contrast-to-noise ratio (CNR) and lower measurement errors than larger voxel sizes (149 μm). The 1x1 detector pixel binning mode with 250 ms exposure time and the optimized window size significantly improve measurement accuracy for both aluminum and polyoxymethylene (POM) components [S4].

b. For multi-material test specimens, I proved that the signal-to-noise ratio (SNR) of air gaps proportionally decreases with the increase of the air gap (from 25 μm to 125 μm) at the interface between aluminum and POM materials, while the grey values of the air gaps show characteristic separation patterns as a function of detector pixel binning mode, voxel size, and rotation mode [S4].

5. Thesis: I have shown that in improving the dimensional accuracy of parts manufactured from polyamide 12 (PA12) by selective laser sintering (SLS), the conscious choice of part orientation in the build space [S5, S6, S7] also has a significant effect alongside CAD model compensation. I verified that a compensation procedure based on X-ray tomography (XCT) measurements using the inverse of the measured deviations not only increases the accuracy of distances between flat surfaces but also corrects the systematic calibration errors of the manufacturing equipment [S5]. In addition, I proved that alongside the effect of compensation, the position of cylindrical surfaces can be significantly improved by choosing the optimal orientation [S8].

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