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Dimensional measurement using X-ray Computed Tomography for additive manufacturing in standardization

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Abstract
Until now, X-ray computed tomography (XCT) has mainly been used for non-destructive testing (NDT) to provide qualitative information about internal geometry and to detect defects in complex parts such as those produced by additive manufacturing (AM). However, to fully assess the conformity of mass-produced parts in industry, their metrological characterisation is also necessary. The complexity of geometries that AM allows manufacturing, particularly internal geometries, prevents the use of surface methods for their metrological characterisation. Therefore, XCT is required for metrology in the AM industry. Although, the metrological performance and traceability of XCT is still a challenge due to the complexity of the dimensional measurement chain involving many influencing factors, the growing need to use XCT for dimensional measurements of AM series production parts in industry must be taken into account. This inexorably requires the production of standards on the topic. Indeed, without standard, the full acceptance of a technique does not happen. Consequently, a preliminary draft standard about dimensional measurements on XCT images (ISO/ASTM NP 52971) has been submitted to ISO TC261/ASTM F42, dedicated to AM, on 13/06/2025. This draft provides a methodology to be followed prior to performing dimensional measurements on 3D volumetric XCT images of AM series production parts. The preliminary draft standard submitted is presented in detail.

Additive manufacturing (AM), X-ray computed tomography (XCT), metrology, dimensional measurement, standardisation

1. Introduction

X-ray Computed Tomography (XCT) spreads out for quality control of parts in industry [1,2], i.e. three-dimensional (3D) visualisation in volume for function testing [3], non-destructive inspection for flaw analysis [4,5], but also metrology for nominal/actual comparison, tolerance analysis, and dimensional measurements [6-13]. This spreading can be explained by the fact that additive manufacturing (AM), producing parts with complex geometries that may contain internal features, is becoming increasingly popular in industry. For metrology of parts conventionally manufactured, without internal feature, surface methods, providing a 3D surface point cloud (such as coordinate measuring machine (CMM), were sufficient. However, surface methods, for complex geometries with internal features, are no longer appropriate. A 3D volumetric non-destructive testing (NDT) method, such as XCT, is required for AM. Indeed, XCT provides an image of the whole volume of a test part (geometric 3D representation of the inside and outside) from which dimensional measurement can be performed.

Performing dimensional measurements on a 3D volumetric XCT image is a very complex process as it involves several steps, each of which being influenced by several factors. This situation considerably complicates the assessment of the dimensional measurement uncertainty evaluation and, until now, have prevented the generalization of an uncertainty evaluation to all dimensional measurements (i.e. to all measurands and to all XCT settings). However, there is a growing need for using XCT systems for dimensional measurements of AM series production parts and, without standards providing a detailed process to validate CT systems for this purpose (in parallel with existing standards VDI/VDE 2630 [14] & ASME B89.4.23 [15]), the full acceptance of the XCT technique for metrology of AM parts will not happen.

Consequently, LNE, in collaboration with Safran, has proposed a preliminary draft standard to ISO TC261/ASTM F42 dedicated to AM (ISO/ASTM NP 52971), on 13/06/2025. This preliminary draft proposes a methodology to be followed prior to performing dimensional measurements on 3D volumetric XCT images of AM series production parts. It aims to validate the dimensional measurements of their measurands of interest and to provide a simplified method for assessing their dimensional measurement uncertainty.

In parallel, LNE offers, on its website, a free interface to quantify the XCT system performance in terms of dimensional measurement accuracy: Quantification of the influence of the XCT system hardware geometry using a reference object and quantification of the uncertainty to attribute to each measurand of a Representative Quality Indicators (RQI). The interface offers as well a validation of the XCT system compliance: Quantification of the uncertainty to attribute to each measurand of a part chosen from the AM series production parts (i.e. specific part).

The paper describes the proposed methodology in detail.

2. Dimensional measurements on a 3D volumetric XCT image

Performing dimensional measurements on a 3D volumetric XCT image involves the following steps:

1) specifying rigorously, with the customer, the measurands of interest in the test part in a defined coordinate system;
2) defining a dimensional measurement protocol, i.e. a measurement strategy;

3) the XCT scan of the test part to get its projections over 360° (2D images). These projections correspond to a mapping of pixels with different grey values representing the absorption of the X-ray beam by the test part;
4) the reconstruction of the 3D volumetric XCT image from the projections, using a dedicated algorithm. This 3D volumetric XCT image is composed of voxels (3D pixels) with different grey values;
5) the surface determination or segmentation to determine the boundary between background and materials. This step enables the internal and external surfaces of the part to be materialised. It is then from these surfaces that the dimensional measurements will be performed or that a mesh file can be generated (e.g. point cloud or set of vertex, most often STL format);
6) the registration of the test part, in the used analysis software, with its Computer-Aided Design (CAD) model to position it into the defined coordinate system (this step can be preceded by a surface exportation, which can be the STL file mentioned above, to process the data in another software);
7) fitting geometrical elements on the features to be measured in the test part;
8) performing the dimensional measurements of the defined measurands according to the predefined dimensional measurement protocol.

3. Proposed methodology in the preliminary draft standard

The proposed methodology to be followed prior to performing dimensional measurement on 3D volumetric XCT images of AM series production parts, in the preliminary draft standard, is divided into two steps:

- Step 1: Qualification of the XCT system performance, in terms of image quality and basic dimensional measurement accuracy, with a reference object and eventually a Representative Quality Indicators (RQI), with the specific part XCT setting under certain environmental conditions. This step leads to the determination of the image quality and its stability over time, the voxel size, and the basic dimensional measurement accuracy of the XCT system;
- Step 2: Validation of the XCT system compliance, in terms of dimensional measurement accuracy, with the specific part, with the chosen XCT setting under the specific environmental conditions. This step leads to the determination of the dimensional measurement uncertainty of each measurand of the specific part. This uncertainty must then be examined in relation to the expected tolerance.

If step 1 does not comply with the set requirements, the XCT system cannot be used for step 2.

The standard does not claim to provide a definitive method to determine XCT dimensional measurement accuracy, which, given the complexity of an XCT process, is not yet established. For the same reason, it is addressed to qualified XCT operators with the support of metrology experts.

These prior qualification and validation processes, which allow dimensional measurements to be carried out on 3D volumetric XCT images of AM series production parts, are valid for a specific part geometry in a given material associated with a chosen XCT setting (magnification & XCT acquisition and reconstruction parameters of the specific part) under specific environmental conditions, for the measurands specified. The qualification process must be reconsidered when the geometry of the part or material or XCT setting or environmental conditions or measurands are too different to be covered by the same qualification.

4. Qualification of the XCT system performance

Before performing dimensional measurements on 3D volumetric XCT images of AM series production parts, the performance of the XCT system shall be qualified. The performance of an XCT system is defined in terms of image quality produced by the XCT system, and dimensional measurement accuracy allowed by the XCT system. The proposed qualification consists in two steps:

1. Quantification of the image quality of the XCT system with the specific part XCT setting under certain environmental conditions to record its initial performance in terms of image quality to be able then to monitor its stability during the operational lifetime of the system;
2. Calibration of the voxel size and quantification of the dimensional measurement accuracy of the XCT system with the chosen XCT setting under the specific environmental conditions to determine its basic performance in terms of dimensional measurement accuracy. This second step consists also in two steps:
   2.1 Calibration of the voxel size and quantification of the influence of the XCT system hardware geometry using a reference object to quantify the basic dimensional measurement accuracy of the XCT system;
   2.2 Quantification of a dimensional measurement uncertainty, per measurand, using a RQI.

All these steps are illustrated in Figure 1.

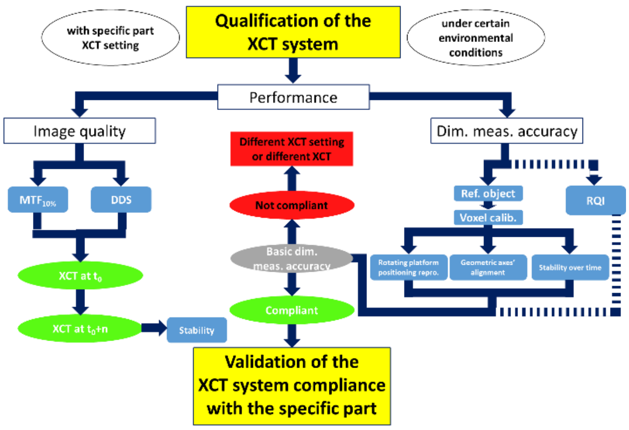

Figure 1. Flow chart presenting the different steps to qualify the XCT system performance

4.1. Quantification of the image quality of the XCT system: initial performance of the system in terms of image quality and monitoring of its stability

According to ASTM E1695 [16], the major factors affecting the quality of a 3D volumetric XCT image are total image unsharpness, contrast, and noise. Geometrical and detector unsharpness limit the spatial resolution of an XCT system, that is, its ability to image fine structural detail in an object. Noise and contrast response limit the contrast sensitivity of an XCT system, that is, its ability to detect the presence or absence of features in an object (to discriminate a contrasting feature from the base). Spatial resolution may be quantified in terms of the Modulation Transfer Function (MTF), and contrast sensitivity may be quantified in terms of the Contrast Discrimination Function (CDF). The relationship between contrast sensitivity and spatial resolution, describing the resolving and detecting capabilities, is given by the Contrast-Detail-Diagram (CDD). These three indicators allow assessing the spatial resolution, contrast sensitivity and the numerical detection limit, i.e. Detail Detection Sensitivity (DDS) that quantify the image quality of an XCT system [17,18]. However, it is important to note that these indicators do not take into account the image artefacts.

The instructions for determining the MTF, CDF, CDD and DDS are provided in ASTM E1695 [16], ASTM E1441 [19] and ASTM WK84836 [20].

The results obtained for the $MTF_{10\%}$ and DDS quantify the performance of the chosen XCT system at t_0. This quantification shall then be determined periodically during the measurement of the AM series production parts to check for any of its deterioration and to monitor the stability of the XCT system over time. Any drift of these factors relative to t_0 during the measurements of the AM series production parts shall remain within defined acceptance criteria (10 %).

4.2. Basic quantification of the dimensional measurement accuracy of the XCT system: voxel size and basic performance of the system in terms of dimensional measurement accuracy

The XCT system compliance to perform dimensional measurement shall be determined through the evaluation of its basic dimensional measurement accuracy. The dimensional measurement accuracy of the XCT system depends on the one hand on its hardware geometry, and on the other on the interaction between the X-ray and the scanned part. To quantify the influence of the hardware geometry, in terms of stability over time and environmental conditions, alignment of geometric axes, and reproducibility of the repositioning of its rotating platform, on dimensional measurement accuracy, a simple reference object including at least two ruby spheres shall be used. This step provides also the voxel size that shall be corrected prior to the quantification of the influence of the XCT system hardware geometry. To quantify the effect of the interaction between the X-ray and the scanned part, a RQI shall be used. This second step, with the RQI, is recommended, but optional as it can be performed directly with the specific part.

These two step quantifications shall be done to ensure that the XCT system reaches the dimensional measurement accuracy expectations on the specific part.

5. Validation of the XCT system compliance

After the basic dimensional measurement accuracy compliance of the XCT systems has been approved with a reference part and eventually a RQI, their compliance shall be validated directly on the specific part (i.e. part chosen from the AM series production parts) with the defined measurement protocol, the chosen XCTs and setting (magnification & XCT acquisition and reconstruction parameters) under the same environmental conditions as in the previous steps, for each specified measurands.

This validation shall be performed for each XCT system and by minimum three operators involved in the dimensional measurement of the AM series production parts. The uncertainty on dimensional measurements of each measurand includes all XTC systems and all operators.

This validation of the compliance of the XCT systems with the specific part consists in several steps:

- Step 1: XCT scan and dimensional measurement on the 3D volumetric XCT image of each measurand of the specific part with the chosen XCT setting under the same environmental conditions as in the previous step (§4);
- Step 2: Full characterization of the whole specific part, ideally under the same environmental conditions, using a reference dimensional measurement method. To date, reference dimensional measurement methods, such as CMM, are surface methods. Therefore, this characterization leads to the characterization of the full surface of the specific part;
- Step 3: Cutting of the specific part in several sections allowing surface accessibility of all measurands of interest;
- Step 4: Full characterizations of each cut section of the specific part using the reference dimensional measurement method;
- Step 5: Registration of the 3D surface characterization of the whole specific part before cutting with the 3D surface characterizations of its different cut sections;
- Step 6: Dimensional measurement of each measurand on the reference registered 3D characterisation;
- Step 7: Determination of the uncertainty on the dimensional measurement for each measurand using the LNE interface;
- Step 8: Discussion in between experts of the results with regards to acceptance criteria.

All these steps are illustrated in Figure 2.

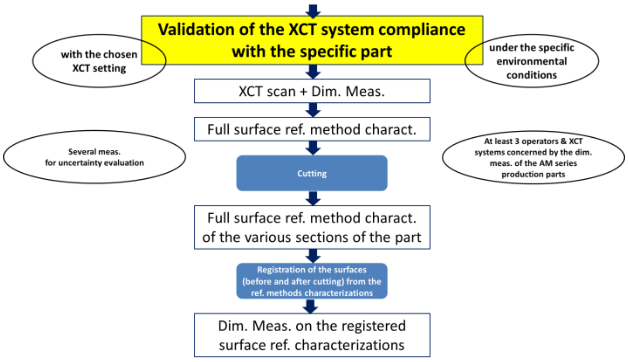

Figure 2. Different steps to validate the dimensional measurement accuracy compliance of the XCT system with the specific part

6. Proposed uncertainty calculation in LNE interface

6.1. Quantification of the influence of the XCT system hardware geometry using a reference object

In the LNE interface, the uncertainty associated to a specific XCT (i) system hardware geometry using a reference object is given by:

$$u_{geo\ XCT_i} = \sqrt{u^2_{mis\ XCT_i} + u^2_{repos\ XCT_i} + u^2_{stab\ XCT_i} + u^2_{ref obj.}}, \quad \textbf{Eq.1}$$

with the standard uncertainties corresponding to:

- the geometric axis's alignment of the XCT system

$$u_{mis\ XCT_i} = \frac{|\max_k(\Delta d_{mis}(pos.k)) - \min_l(\Delta d_{mis}(pos.l))|}{2\sqrt{3}}, \quad \textbf{Eq.2}$$

- the XCT system repositioning reproducibility

$$u_{repos\ XCT_i} = \frac{|\max(\Delta d_{repos}) - \min(\Delta d_{repos})|}{2\sqrt{3}}, \quad \textbf{Eq.3}$$

- the XCT system stability over time

$$u_{stab\ XCT_i} = \frac{|\max_k(\Delta d_{stab}(t_k)) - \min_l(\Delta d_{stab}(t_l))|}{2\sqrt{3}}, \quad \textbf{Eq.4}$$

Denoting:

$u_{ref\ obj.}$	Dimensional measurement uncertainty of the reference object provided by the calibration certificate;
Δd_{mis}	Bias between XCT measurements of the reference object scanned several times over the entire volume, and the reference measurement;
Δd_{repos}	Bias between XCT measurements of the reference object scanned several times for the same positioning of the rotating platform, but moving it first up/down, then left/right and finally front/rear in between each scan, and the reference measurement;

Δd_{stab} Bias between XCT measurements of the reference object scanned regularly over 3 days.

6.2. Quantification of the uncertainty to attribute to each measurand of the specific part

Regarding the dimensional measurement uncertainty for each measurands (k), ISO 5725-2 [21] and ISO 5725-4 [2] provide practical guidance for evaluating the accuracy of a measurement method. The International vocabulary of metrology (VIM) defined accuracy as "closeness of agreement between a measured quantity value and a true quantity value of a measurand". Although the accuracy is a qualitative characteristic in these ISO standards, and generally in the validation method field, it is designated by the two properties: precision and trueness. According to VIM, trueness refers to "closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value", whereas precision evaluates "closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions". Therefore, the uncertainty for each measurand (k) of the specific part, including all operators (p) and all XCT systems (i), is given in the interface by:

$$u(meas_k) = \sqrt{u^2(trueness_k) + u^2(precision_k)} + \frac{|Bias(meas_k)|}{2} \quad \textbf{Eq.5}$$

where $u(trueness_k)$is the dimensional measurement uncertainty attributed to measurand (k) of the specific part, provided by the calibration certificate. The bias $(Bias(meas_k) = \bar{\bar{x}}_{all\ op.\&XCT\ k} - x_{refspec.part\ k})$ is not corrected therefore it is added to the uncertainty,

$\bar{\bar{x}}_{all\ op.\&XCT\ k}$ Average of all measurements of measurand k considering all p operators and all XCT systems;

$x_{refspec.part\ k}$ Reference dimensional measurement of measurand k provided by the calibration certificate.

$$u^2(precision_k) = max_i(u^2_{geo\ XCT_i}) + max_i\left(u^2(resolution_{XCT_i})\right) + s^2_{Rk} \quad \textbf{Eq.6}$$

with:

$$u(resolution)_{XCT_i} = \frac{1}{4\sqrt{3}\mathrm{MTF}_{10\%}} \quad \textbf{Eq.7}$$

and

$$s^2_{Rk} = s^2_{rk} + s^2_{L\ op.k} + s^2_{L\ XCTk} \quad \textbf{Eq.8}$$

In which, the repeatability standard deviation is given by:

$$s_{rk} = \sqrt{\frac{\sum_{j=1}^{p}(n_{jk}-1)s^2_{jk}}{\sum_{j=1}^{p}(n_{jk}-1)}} \quad \textbf{Eq.9}$$

The standard deviation of operator effect is given by:

$$s_{Lop.k} = \sqrt{\frac{s^2_{dk}-s^2_{rk}}{\bar{\bar{n}}_k}} \quad \textbf{Eq.10}$$

with:

$$s_{dk} = \sqrt{\frac{1}{p-1}\sum_{j=1}^{p} n_{jk}\left(\bar{x}_{jk} - \bar{\bar{x}}_k\right)^2},$$

$$\bar{\bar{n}}_k = \frac{1}{p-1}\left[\sum_{j=1}^{p} n_{jk} - \frac{\sum_{j=1}^{p} n_{jk}{}^2}{\sum_{j=1}^{p} n_{jk}}\right] \text{ and } \bar{\bar{x}}_k = \frac{\sum_{j=1}^{p} n_{jk}\bar{x}_{jk}}{\sum_{j=1}^{p} n_{jk}}.$$

In which:

j indicates a specific operator;
n_{jk} Number of measurements for operator j and measurand k;
s_{jk} Standard deviation for operator j and measurand k;
$\bar{x}_{jk}$ average of measurements for operator j and measurand k;

Similarly, for the standard deviation of XCT effect $s_{LXCT\ k}$.

7. Conclusion

The preliminary draft standard: ISO/ASTM NP 52971 "AM — Non-destructive testing and evaluation — Dimensional measurements on X-ray Computed Tomography images", submitted to ISO TC261/ASTM F42, dedicated to AM, on 13/06/2025, was presented. The proposed methodology to be followed prior to performing dimensional measurements on 3D volumetric XCT images of AM series production parts was detailed.

After applying this protocol, if the performance of the XCT systems is demonstrated and the results of the characterisation of the specific part are within the tolerance interval, the XCT systems can be selected to carry out dimensional measurements of the AM series production parts:

- with the given XCT setting of the specific part (magnification & XCT acquisition and reconstruction parameters);
- in a fixed environmental condition range;
- with the defined measurement protocol;
- for the specified measurands;
- by the XCT operators that performed the validation on the specific part.

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