Uncertainty of CT dimensional measurements performed on metal additively manufactured lattice structures

Filippo Zanini[1], Marco Sorgato[2], Enrico Savio[2], Simone Carmignato[1]

[1]University of Padova, Stradella San Nicola 3, Vicenza, Italy, e-mail: filippo.zanini@unipd.it | simone.carmignato@unipd.it

[2]University of Padova, via Venezia 1, Padova, Italy, e-mail: marco.sorgato@unipd.it | enrico.savio@unipd.it

Abstract

Metal parts with controlled lattice structures can effectively be produced via additive manufacturing (AM) technologies. However, one of the critical aspects of metal AM products is the dimensional and geometrical accuracy. X-ray computed tomography (CT) can be applied to enable advanced control methods that are fundamental for improving the geometrical characteristics and the quality of complex metal AM parts. In this work, Ti6Al4V lattice structures produced by laser powder bed fusion were analysed using a metrological X-ray CT system. Two different approaches for determining the uncertainty of dimensional measurements based on the CT reconstructed volumes were implemented and compared: the "substitution method" and the "multiple measurements" approach. Advantages and limitations of both approaches are identified and discussed.

Keywords: X-ray computed tomography, additive manufacturing, lattice structures, dimensional metrology, uncertainty

1 Introduction

Metal additive manufacturing (AM) technologies are increasingly used in several industrial sectors (e.g. aerospace, biomedical), especially thanks to the capability of fabricating components having complex geometry and high structural complexity [1]. Among the AM processes, laser powder bed fusion (LPBF) – which produces metal parts directly from computer aided design (CAD) data by the selective melting of successive layers of metal powders – has proven to be particularly suited to produce strong, lightweight and complex metallic lattice structures, whose fabrication is often not possible through conventional manufacturing techniques (e.g. machining and casting) [2]. Lattice structures are defined as "*three-dimensional geometrical arrangement composed of connective links between vertices (points) creating a functional structure*" [3] and have a great potential, for example, in the field of biomedical implants, because implants with a porous structure show reduced stress shielding and improved osseo-integration in comparison to traditional fully dense structures [4]. However, LPBF products are typically characterised by geometrical errors, internal defects and complex surface topographies, which may lead to mechanical properties degradation and product failure [5]. In order to effectively improve the AM process, adequate measuring techniques and procedures are needed to provide accurate dimensional characterization of the AM products [6]. In this context, X-ray computed tomography (CT) can be used as an advanced measuring technique that enables non-destructive dimensional analyses of both external and internal geometries and features, which in most cases are not viable with traditional measuring techniques [7]. Moreover, CT is also capable of reconstructing the three-dimensional model of the scanned object with high surface digitization in a relatively short time and to perform simultaneously different kind of analyses, including coordinate metrology, porosity analysis and surface topography evaluation [8, 9]. This work, in particular, addresses the application of CT for dimensional quality evaluation of AM lattice structures. Such an application has already been studied in literature with several aims: to improve geometrical and mechanical control of LPBF lattice structures [10], to evaluate structural deviations of the as-built structures with respect to the as-designed geometry [11], and to improve finite element analyses of the stress distribution at the strut junctions with the benefit to base the simulations not on an ideal geometry but on the actual one [12]. However, although CT was proven to be an effective tool capable of providing an information-rich geometrical description of AM lattice structures, the uncertainty of CT dimensional measurements is often critical and not easy to determine [13]. The objective of this work is to investigate the possible application of two approaches for the uncertainty determination and the correction of systematic errors for CT measurements of metal AM lattice structures. The first approach is the so-called substitution method, which is well known for CT dimensional measurements, but limited for complex objects by the fact that it is based on the availability of calibrated workpieces similar to the measured workpieces [14]. The second approach is based on the multiple measurements strategies, and is newly proposed for CT metrology in this work, adapting it from a method that is proposed and still under investigation for coordinate measuring machines (CMMs) [15].

2 Lattice structures and CT measurements

This section briefly describes the investigated lattice structures (Section 2.1), the instrumentation and setting related to the CT scans (Section 2.2) and the definition of measurands (Section 2.3).

2.1 Investigated samples

In this work, specimens produced by LPBF of Ti6Al4V alloy characterized by specific lattice designs (i.e. periodic structures determined by cubic cells) were used as case study. They were designed to have density and mechanical properties comparable to those of trabecular bone. Figure 1 (a) shows one of these specimens as an example.

2.2 CT scanning

The lattice structures introduced in Section 2.1 were scanned by a metrological CT system (Nikon Metrology MCT225), characterized by micro-focus X-ray source with minimum achievable focal spot size of 3 µm, 16-bit X-ray detector with a 2000×2000 pixel grid, controlled cabinet temperature (20 ± 0.5 °C) and maximum permissible error (MPE) for length measurements equal to (9 + L/50) µm (where L is the length in mm). The scanning parameters are reported in Table 1. Figure 1 (b) shows an example of CT reconstructed volume and Figure 1 (c) reports two examples of cylindrical features extracted from the CT volume. The analysis and visualization software VGStudio MAX 3.2.3 (Volume Graphics GmbH) was used to perform dimensional measurements by association of geometrical elements (e.g. cylinders) to the features of interest, according to the measurands defined in Section 2.3.

2.3 Definition of measurands

The measurands investigated in this work were chosen considering dimensional characteristics that can be critical for mechanical and fatigue properties, i.e. dimensions of cylindrical features composing the lattice structure and structural deviations with respect to the CAD geometry. Concerning the cylindrical features, horizontal and vertical elements were distinguished, since they can be characterized by different dimensions and surface roughness depending on the sample orientation with respect to the AM building direction.

A total of 15 vertical and 15 horizontal features were measured, selected within three different regions of the sample: middle, top and bottom. Three circles were fit on each vertical and horizontal feature, as illustrated in Figure 1 (c), to compute their diameters. The same surface points used to fit such circles were then used to fit a cylinder for each feature. Three-dimensional distances were measured between the points obtained from the intersection of each cylinder axis with planes: axes of vertical cylinders were intersected with parallel horizontal planes at specific locations, and axes of horizontal cylinders were intersected with vertical planes at specific locations.

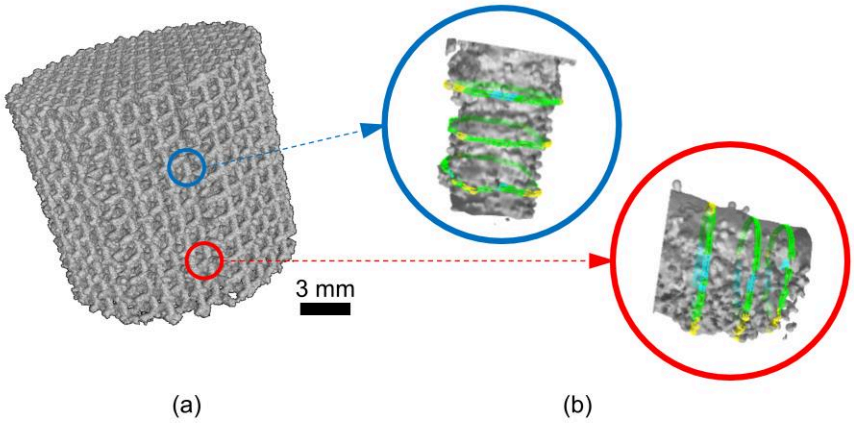

Figure 1: CT reconstructed volume of a Ti6Al4V LPBF lattice structure (a) and examples of cylindrical features (vertical = blu circle; horizontal = red circle) extracted from the CT model where three circles were fit to compute their diameter (b)

Table 1: CT scanning parameters

Parameter	Value
Voltage	180 kV
Current	38 µA
Power	6.8 W
Exposure time	2000 ms
Frames per projection	1
Nr. of projections	1500
Physical filter	Copper, 0.1 mm
Voxel size	9 µm

3 CT measurement uncertainty

Two different methods for assessing the uncertainty of CT dimensional measurements performed on lattice structures are investigated in this work: the substitution approach (described in Section 3.1) and the multiple measurements approach (described in Section 3.2).

3.1 Substitution approach

The first approach is based on the experimental procedure described in the guideline VDI/VDE 2630-2.1 [14], which is a well-known method for the uncertainty assessment in CT dimensional metrology [16]. This approach requires the availability of calibrated samples (with sufficiently low calibration uncertainty) similar to the objects to be measured. In the case of AM lattice structures, an important limitation of the substitution approach is related to the unavailability of appropriate reference samples, especially due to difficulty of performing accurate calibration measurements on highly-rough structures which in most cases are inaccessible from the outside. For this reason, a reference sample was designed and produced to meet the similarity conditions with respect to Ti6Al4V lattice structures produced by LPBF. The reference sample is an assembly of two bodies: a main body (see Figure 1 (a)) and a counterpart (see Figure 1 (b)), where the counterpart and the main body are assembled together). Both these bodies were machined starting from a bulk Ti6Al4V bar, via turning and ultra-precision milling operations. The main body is characterized by six pins with same nominal diameter of 0.4 mm (comparable to the nominal diameter of cylindrical features of the investigated lattice structures) and different heights ranged between 0.8 mm and 2 mm. The pins are disposed along a spiral path in order to randomize the relative distances between each couple of pins. The counterpart has the double function of (i) increasing the maximum thickness to be penetrated by the X-ray beam up to the maximum thickness of the lattice structures (to allow the use of the same CT scanning parameters) and (ii) allowing a double possibility for measuring the pins: as non-accessible internal features measured by CT when the counterpart is assembled, and as accessible external features measured by CMM when the counterpart is removed. The measurands were defined similarly to those defined in Section 2.3 for the lattice structures. Equally-spaced circles were measured for each pin, and the surface points used to fit such circles were then used to fit a cylinder for each pin. Three-dimensional distances were measured between points obtained from the intersection of each cylinder axis with planes aligned on the base plane (i.e. the plane where the pins lie). In addition, the heights of pins were measured as the distances between the base plane and the top pin's planes at the pins' axes. The calibration was performed according to the same definition of measurands, using a tactile CMM Zeiss Prismo Vast 7 (MPE = (2.2+L/300) µm, with L is the length in mm). The same measurements were conducted with CT, on the CT reconstructed volume obtained from repeated CT scans of the object (using the same scanning parameters reported in Table 1). For each measurement, the uncertainty was determined as recommended in the guideline VDI/VDE 2630-2.1 [14]. The similarity conditions requested by the guideline between lattice structures and reference object are well respected in terms of material, size and geometry, but not for the surface roughness and form errors that are consistently larger for the lattice structure's cylindrical features than for the reference object's pins. For this reason, the surface roughness and form errors contributions were taken into account among the uncertainty contributions, based on a previous work [17].

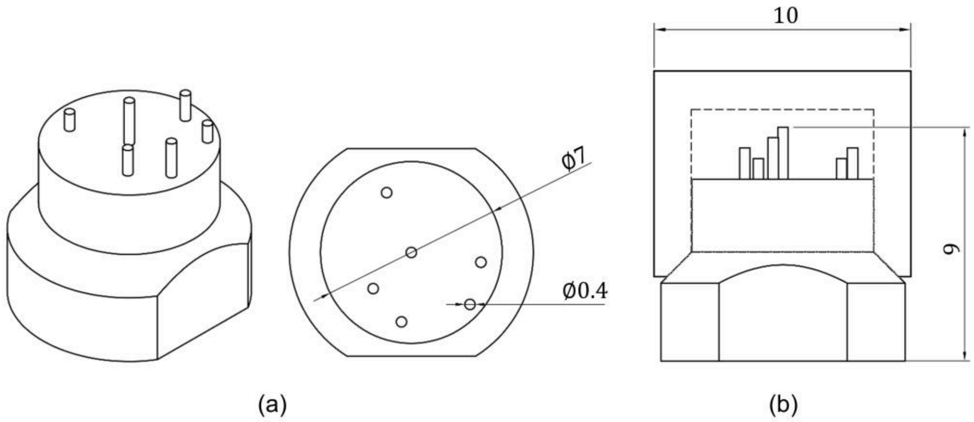

Figure 2: Representation of the reference object produced to apply the substitution approach: main body (a) and assembly with the counterpart (b).

3.2 Multiple measurements approach

The second approach (which is newly applied in this work to CT metrology) for the uncertainty determination is an adaptation of the "multiple measurements" strategy that was previously proposed for CMMs [15] and is currently under refinement within the European project EUCoM (*Evaluating Uncertainty in Coordinate Measurement* [18]). The main advantage of this approach is that it is not limited by the unavailability of reference samples, which is a common issue for very complex workpieces as the lattice structures investigated in this work. The basic principle of the "multiple measurement" approach is to perform repeated measurements by re-orienting multiple times the object within the measurement volume, in order to introduce and stimulate the variation of geometrical errors and other errors (such as those originated by image artefacts that typically influence CT scans [7]). The investigated object has to be representative of objects that are typically inspected (for example, other lattice structures with same material and comparable dimensions). Figure 3 shows schematically the five orientations chosen to scan the lattice structure to estimate the effect of CT geometrical errors and of image artefacts. Attention was given to the choice of "natural" alternative positions with good measuring conditions.

To establish the traceability to the unit of length (metre), the "multiple measurement" approach requires additional tests to be performed using calibrated length and form standards (which in this case are not required to be similar to actual workpieces). To this end, a calibrated artefact characterized by six 1 mm-spheres arranged on a carbon support and with different calibrated center-to-center distances was used. The artefact was scanned at three different positions in the measuring volume, using the same parameters reported in Table 1.

The "multiple measurement" approach was applied also to the reference sample presented in Section 3.1, as if it was the object under investigation, to allow the evaluation of metrological compatibility [19] between CT measurements and reference measurements.

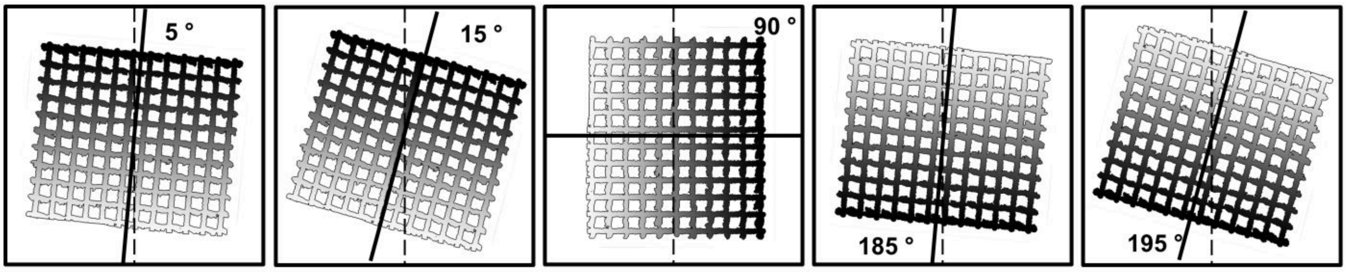

Figure 3: Representation of the five orientations of the lattice structure within the X-ray detector field of view: 5°, 15°, 90°, 185°, 195°.

4 Results and discussions

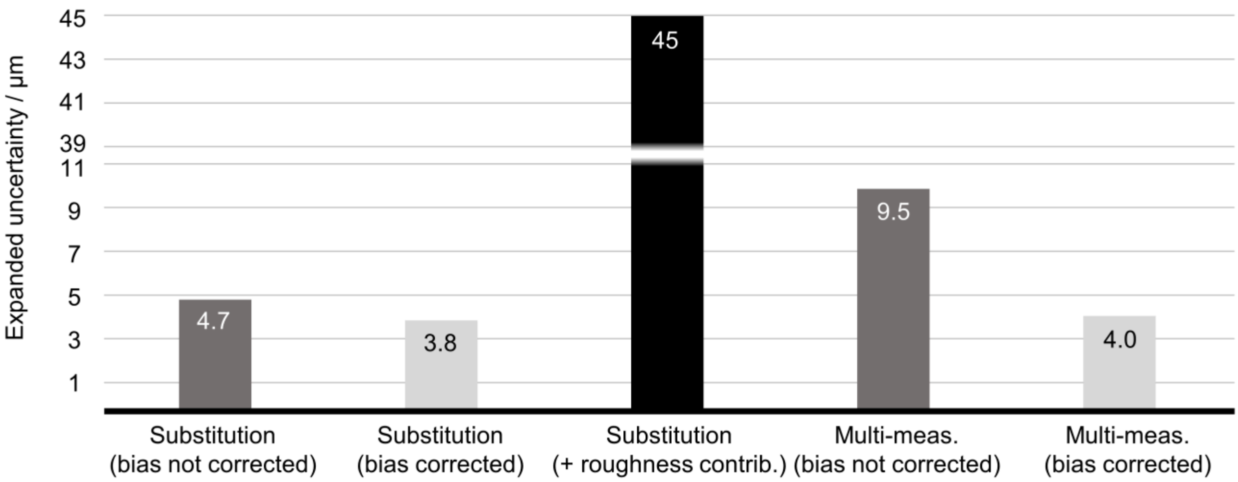

Figure 4: Expanded uncertainty (95 % confidence interval) determined with different approaches for the CT measurement of lattice structure circles diameters (nominally equal to 0.4 mm) in the case of horizontal cylindrical features.

The measurement uncertainty was determined using the two approaches described in Section 3.1 and 3.2 for all the investigated measurands and for all the samples (diameters and three-dimensional point-to-point distances for the lattice structure; diameters, three-dimensional point-to-point distances and pins heights for the reference object). Moreover, the uncertainty was determined in two different scenarios: in the first one, the bias was not corrected but considered as an uncertainty contribution; in the second the bias was instead corrected. In the substitution approach, the bias is calculated as difference between average measured value and reference value, while in the "multiple measurement" approach it includes the contributions of scale error and probing error of size. The surface roughness effect was treated as a separate uncertainty contributor in this work, to better underline its impact on the uncertainty determination using the substitution approach. Figure 4 shows as an example the expanded uncertainty values (95 % of confidence interval) obtained in the above-depicted cases for the CT measurement of lattice structure circles diameters (for horizontal cylindrical features). If the roughness and form errors contributions are not taken into account, the "multiple measurement" approach leads to higher uncertainties than the substitution approach, especially in the case of uncorrected bias. The difference is far lower when the bias is corrected instead of being included in the uncertainty. However, differently from the substitution approach, the "multiple measurement" approach is not based on the measurement of a reference calibrated object, hence it does not require to add the effect of form errors and surface roughness as a separate additional contribution. For this reason, in cases where the surface roughness and the form errors are particularly high, the substitution approach can lead to

overestimate the uncertainty. Similar results were obtained for the other measurands, so that the same considerations hold for them as well.
Besides the comparison between the two approaches, the "multiple measurement" approach was applied also to the reference object in order to assess the metrological compatibility between CT measurements and reference measurements, by computation of the normalized error E_N (see Eq. 1) [19]: when E_N is below 1 a good agreement exists between the two compared results, while if E_N is above 1 the results are not in good agreement.

$$E_N = \frac{|Value_{CT} - Value_{CAL}|}{\sqrt{U_{CT}^2 + U_{CAL}^2}} \quad \text{(Eq. 1)}$$

In the case of bias not corrected, for each measurand, the E_N was found to be below 1. However, in the case of bias corrected, the E_N was below 1 in all cases except for one. Moreover, the E_N values were observed to slightly increase after the bias correction. Thus, the error correction might be non-optimal. Another open issue is related to the choice of multiple orientations, because the relationship between sample orientation and impact of CT errors and artefacts on the measurement uncertainty have to be studied more in depth. Moreover, the chosen orientations must be varied depending on the geometry and dimensions of the object to be scanned, and this limits the possibility to define a generalised approach with standard orientations. For example, in the case of high-aspect-ratio samples, a 90° rotation from one orientation to another might be impossible or inadequate, as the maximum thickness to be penetrated by X-rays could become too large.
Another relevant aspect emerged from the results obtained in this work is that the "multi measurement" approach might overestimate or underestimate the uncertainty, depending on the specific measurement cases. Consequently, future work is needed to refine the approach and study how it can be adapted to CT measurements.

5 Conclusions

This work describes the experimental investigation of two approaches to determine the uncertainty of CT dimensional measurements performed on complex AM lattice structures. Both experimental procedures delivered comparable uncertainty statements. Advantages and limitations of both approaches were pointed out. In particular, the main advantage of the "multiple measurement" approach is that it does not require the use of calibrated artefacts similar to the objects that are typically measured. This is interesting especially for AM components, which are typically characterized by very complex geometries, including non-accessible geometries and features that are difficult or even impossible to be calibrated using conventional measuring techniques. Nonetheless, the fabrication of task-specific reference objects fulfilling the similarity requirements of the substitution approach may be difficult for complex structures and also expensive due to costs related to design, fabrication and calibration.
In addition, the effect of form errors and surface roughness (which are typically very high in AM parts) on the comparison between CT measurements and calibration measurements are not taken into account as additional separate contributions. In principle, this is an advantage with respect to the substitution approach, but further investigations are needed to better understand if the "multiple measurement" approach gives sufficient weight to the effect of form errors and surface roughness.
The "multiple measurement" approach was applied also to the reference object developed in this work, to enable the evaluation of metrological compatibility through the computation of normalized errors. The normalized errors were found to be below 1 in almost all cases. The open issues of the "multiple measurement" approach were also discussed, including the possible non-optimal error correction and the difficulty related to the choice of multiple orientations (which are difficult to standardize because should vary depending on the object geometry and dimensions). Future work is needed to improve the understanding of how the method should be applied to ensure reliable uncertainty determination and correction of systematic errors. In addition, since the experiments conducted in this work were limited to a specific geometry, further investigations are needed to extend the research to other case studies.

Acknowledgments

This work has received funding from University of Padova, project Nr. BIRD188872/18, and from the European Union, H2020-EMPIR 17NRM03 EUCoM - Standards for the evaluation of the uncertainty of coordinate measurements in industry.

References

[1] Schmidt M. et al (2017). Laser based additive manufacturing in industry and academia. *CIRP Annals Man. Tech.* 66/2:561-583.
[2] Beyer C., Figueroa D. (2016). Design and analysis of lattice structures for additive manufacturing. *Journal of Manufacturing Science and Engineering*. 138 121014.
[3] ISO/ASTM FDIS 52900:2019 - Additive manufacturing — General principles — Part 1: Vocabulary and fundamental concepts

[4] Arabnejad S., Johnston R. B., Pura J. A., Singh B., Tanzer M., Pasini D. (2016). High-strength porous biomaterials for bone replacement: A strategy to assess the interplay between cell morphology, mechanical properties, bone ingrowth and manufacturing constraints. *Acta biomaterialia*. 30, 345-356.

[5] Gibson I., Rosen D. W., Stucker B. (2015). Additive manufacturing technologies. *Springer International Publishing.*

[6] Leach R. K., Bourell D., Carmignato S., Donmez A., Senin N., Dewulf W. (2019). Geometrical metrology for metal additive manufacturing. *CIRP Annals Man. Tech.*, 68/2:677-700.

[7] Carmignato S., Dewulf W., Leach R. (2018). Industrial X-ray computed tomography. *Springer International Publishing*.

[8] Thompson A., Maskery I., Leach R. K. (2016). X-ray computed tomography for additive manufacturing: a review. *Measurement Science and Technology*, 27(7), 072001.

[9] Zanini F., Pagani L., Savio E., Carmignato S. (2019). Characterisation of additively manufactured metal surfaces by means of X-ray computed tomography and generalised surface texture parameters. *CIRP Annals Man. Tech.* 68/1: 515-518.

[10] Van Bael S., Kerckhofs G., Moesen M., Pyka G., Schrooten J., Kruth, J. P. (2011). Micro-CT-based improvement of geometrical and mechanical controllability of selective laser melted Ti6Al4V porous structures. *Materials Science and Engineering: A*, 528(24), 7423-7431.

[11] Martz H. E. et al. (2014). CT to Evaluate Distortions in Stainless Steel AM Structures. Proceedings of ASPE Spring Topical Meeting 2014: Dimensional Accuracy and Surface Finish in Additive Manufacturing, Berkeley, California (pp. 71-75).

[12] Dallago M., Winiarski B., Zanini F., Carmignato S., Benedetti M. (2019). On the effect of geometrical imperfections and defects on the fatigue strength of cellular lattice structures additively manufactured via Selective Laser Melting. *International Journal of Fatigue.* 124, 348-360.

[13] Sbettega E., Zanini F., Benedetti M., Savio E., Carmignato S. X-ray computed tomography dimensional measurements of powder bed fusion cellular structures. Proceedings of euspen's 18th International Conference & Exhibition, Venice, Italy, June 2018.

[14] VDI/VDE 2630 - 2.1:2015 - Computed tomography in dimensional measurement – Determination of the uncertainty of measurement and the test process suitability of coordinate measurement systems with CT sensors. VDI/VDE Society for Metrology and Automation Engineering (GMA), Duesseldorf.

[15] Trapet, E., Savio, E., De Chiffre, L. (2004). New advances in traceability of CMMs for almost the entire range of industrial dimensional metrology needs. *CIRP Annals Man. Tech.* 53/1: 433-438.

[16] Bartscher, M., Sato, O., Härtig, F., Neuschaefer-Rube, U. (2014). Current state of standardization in the field of dimensional computed tomography. Measurement Science and Technology 25(6):064013.

[17] Carmignato S., Aloisi V., Medeossi F., Zanini F., Savio E. (2017). Influence of surface roughness on computed tomography dimensional measurements. *CIRP Annals Man. Tech.* 66/1: 499-502.

[18] http://eucom-empir.eu/, accessed on 2019-12-23.

[19] ISO/IEC 17043:2010, Conformity assessment — general requirements for proficiency testing, ISO, Geneva.