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Capabilities of industrial computed tomography in the field of dimensional measurements

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A B S T R A C T

The paper discusses the capabilities of industrial computed tomography (CT) in the field of dimensional measurement of products with close tolerances. Computed tomography is a method that allows inspection and measurements of both reachable and unreachable characteristics which makes it very desirable and interesting for application in wide range of industries. In order to evaluate the quality of measurement results obtained by industrial CT, two objects with the same geometry, and made from different materials, were measured. Results obtained with CT were compared with the results obtained by coordinate measuring machine, which were considered to be reference values, and deviations between the results have been analysed. Measurements were repeated five times under repeatability conditions. Repeatability is expressed quantitatively in terms of the dispersion characteristics of the results. Statistical analysis showed that in majority of cases, there were no statistically significant differences between measurement results of equal characteristics obtained at different materials. Obtained deviations in the research could be explained by the fact that the measurements were performed at the industrial CT for general applications. Much better results can be achieved by using a metrology CT device.

A R T I C L E   I N F O

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1. Introduction

Computed tomography (CT) is a method that uses X-ray in order to obtain information about inner and outer geometry and characteristics of inspected objects. It is a well-known method and has been used in medicine and material inspection for over 30 years but its application in dimensional measurements began only about 10 years ago [1]. It is a method with a lot of advantages, which makes it very desirable for industrial purposes of dimensional measurement. Nowadays, requirements on precision and accuracy of production are more rigorous and ever-increasing. There is also a growing need for measurement of objects with more complex geometry and forms [2, 3]. Except standard materials recognized in the industry field, which refers mostly to metals and alloys, great importance is given to application of new materials with better properties and possibilities. The emphasis is on the use of different types of polymers, and in connection to that, different manufacturing methods. In addition to classical metal cutting methods, use of additive manufacturing technology is also increasing. Development and implementation of additive technologies requires development and application of non-destructive inspection and measurement methods. For that reason, the application of industrial CT systems is becoming the basic and foremost requirement [4].

The most significant advantage of computed tomography is the possibility of getting information about internal and external dimensions of inspected object, at the same time, with only one scanning process and without the need to destroy the object [3, 5]. Another advantage, compared to other inspection methods, is the fact that it is suitable for inspection of parts in assembled state without disassembling them [1]. This is of great importance in cases when all parts in disassembled state are manufactured correctly, but do not work properly after being assembled. Furthermore, industrial CT systems enable both dimensional measurements and material analysis to be conducted on the same model. This is especially important when new materials are used in a production process. As such, CT systems are very desirable in many different industries.

However, apart from many advantages, CT dimensional measurement method has also some disadvantages. The main problem for its usage in the field of dimensional measurement is the fact that measurement uncertainty of results is not evaluated, due to the many influential factors in the whole measurement process [6]. This means that metrological traceability is not achieved. In order to assess measurement uncertainty, influence parameters need to be identified and classified. Classification of influence parameters can be done in many different ways. Welkenhuyzen et al [7] proposed dividing influence parameters to: influence of X-ray source, influence of rotation table and workpiece, influence of detector and data processing parameters. Furthermore, Hiller and Reindl [8] divide influence parameters into five groups: CT system, method, test object, environment and human. Another classification of influence parameters can be proposed, according to the step of measurement process. Since the whole CT measurement process can be divided into three sub-processes, where the first sub-process implies scanning of the inspected part, the second one 3D model generation and the third consist of conducting measurements on reconstructed model, influence parameters can be classified into three subclasses: parameters influencing the CT scanning process, parameters influencing reconstruction process and parameters influencing measurement of the model (Fig. 1). CT dimensional measurements are limited by possibilities of CT scanning device, as well as by software tools used for reconstruction and data processing, meaning that operator has great influence on measurement results and measurement uncertainty of obtained results. Operator influence is present throughout the whole CT measurement process, e.g. during selection of CT setups or placing object on rotational table, choosing filters in 3D reconstruction and in data evaluation, and in selecting measurement approach and mathematical algorithm to fit the simple geometry objects. At the moment, use of CT device for industrial measurements largely depends on operator's experience and knowledge. For this reason, estimation of measurement uncertainty is essential and of utmost importance, as well as defining standard procedures for CT measurements.

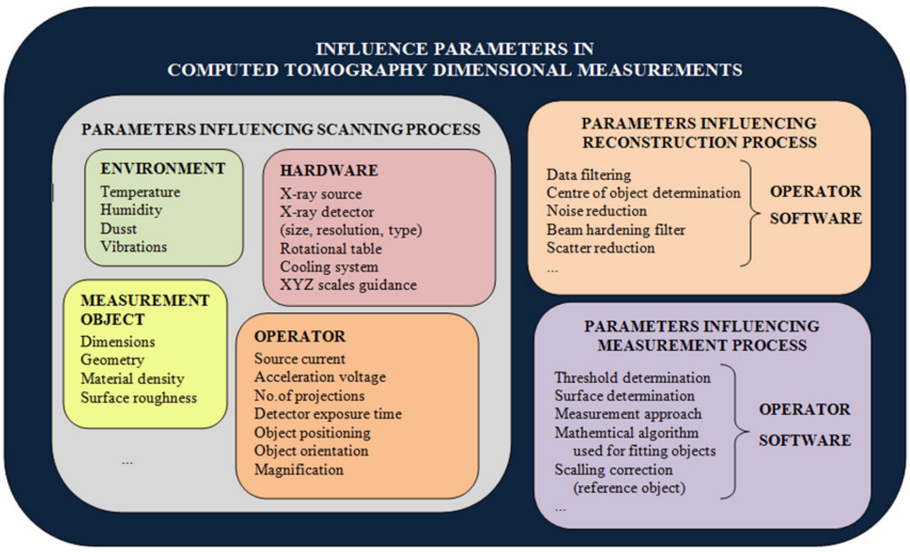

Fig. 1 Influence parameters in CT dimensional measurements

The authors [8-10] evaluate measurement uncertainty in several ways: according to GUM - *Guide to the Expression of Uncertainty in Measurement* [11], where influence of all parameters that affect measurement system has to be determined; with use of computer simulation [12] or by empirical methods that involve use of calibrated workpieces i.e. substitution method [13]. Some authors use the maximum permissible error value (MPE) as an estimator of measurement uncertainty.

This paper researches capabilities of industrial CT device for purposes of dimensional measurements. Two cylinders with the same geometry, made of two different materials were measured and observed. Chosen cylinder geometry represents object where difference in dimensions in different axes is significant, which makes it interesting for the research. Experimental research consisted of dimensional measurements of samples with usage of tactile coordinate measuring machine (CMM) and CT scanning of investigated objects. Results obtained by CT measurements are expressed and observed as deviations from tactile coordinate measurement results which are considered to be reference values. Also, statistical analyses of obtained results were conducted.

2. Materials and method

2.1 Measurement object

Measurements were conducted on two specially shaped cylinders as shown in Fig. 2.

The idea behind the design of such an object was to create an object that will allow for as many different types of measurement and geometrical characteristics as possible. Since the object material has in previous researches [7, 8] been identified as one of the major parameters that influence results, objects for this experiment have been made from two significantly different materials in terms of material density. Cylinder 1 is made of polyamide 6 (PA 6) whose density is 1.4 g/cm^3, and cylinder 2 is made of aluminium with approximately twice as high density, 2.7 g/cm^3. The object was dimensioned based on recommendations for overall penetration depth of an installed CT system [14]. Furthermore, because of the fact that measurement is conducted by fitting simple geometry objects (planes, spheres, cylinders, etc.), the idea was to construct such an object where numerous relationships between different simple objects could be investigated and measured. Except dimensional characteristics, the object is suitable for measurement and investigation of different geometrical characteristics. In this research, only dimensional characteristics were observed. Those were following six different characteristics: outer diameter D, inner diameter d, cylinder length h, distance between two holes l_1, distance between a plane and the centre of a hole l_2 and distance between planes l_3. Fig. 3 shows a drawing of measured objects with the observed measurands.

a) b)

Fig. 2 Measured objects: a) Cylinder 1; b) Cylinder 2

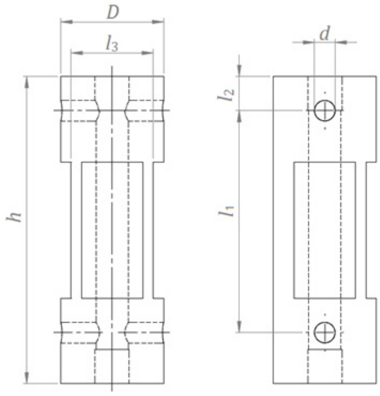

Fig. 3 Measured object with noted measurands

2.2 CMM measurement method

Reference measurements were conducted by coordinate measuring machine Tesa Micro Hite 3D shown in Fig. 4 and measurements were done in software CMM Manager 3.6.

Measurement results with related measurement uncertainties are given in Table 1. Measurement uncertainty in CMM measurements can be conducted in a few ways [15, 16], here CMM measurement uncertainty evaluation is performed in accordance with the Supplement 1 to the 'Guide to the Expression of Uncertainty in Measurement'—Propagation of Distributions Using a Monte Carlo Method which is abbreviated as JCGM 101 [12].

Fig. 4 Coordinate measuring machine Tesa Micro Hite 3D

Table 1 Reference values for cylinder

Measurand	Symbol	Measured results, mm Cylinder 1	Measured results, mm Cylinder 2	Expanded measurement uncertainty U, k = 2, P = 95 % , µm
Cylinder length	h	89.992	90.066	3
Outer diameter	D	29.986	30.016	3
Inner diameter	d	6.010	6.006	3
Distance between two holes	l_1	65.030	64.972	3
Distance between a plane and the centre of one hole	l_2	9.982	10.019	3
Distance between planes	l_3	24.005	23.932	3

2.3 CT measurement method

Whole CT measuring process consists of CT scanning process, 3D modelling process and data evaluation process. CT scanning was conducted on Nikon X TH 225 (Fig. 5), equipped with 225 kV microfocus X-ray source with a tungsten target and 14 bit Varian 4030 Flat Panel Detector [17].

Fig. 5 Industrial CT device – Nikon X TH 225

Measurement process for each cylinder was repeated five times, while all parameters during scanning process were kept constant. Measurements were taken in the same day, by the same operator, on the same measurement device i.e. under repeatability conditions. Quality of results depends on quality of 2D images [18], which means that CT system setup is of great importance. Since there is no prescribed standard for conduction of CT measurements, scanning settings are based on operator's knowledge and experience. Considering the object's geometry, size and material, different setups were determined for each cylinder (given in Table 2). Also, a slightly tilted orientation of object during scanning process was applied.

Object was placed on polystyrene fixture, invisible for the chosen scanning setups. The same fixture was used for both cylinders ensuring the same position of cylinder 1 and cylinder 2 during scanning process. Object orientation during scanning process can be seen in Fig. 6.

Table 2 Scanning parameters

Parameter	Unit	Cylinder 1	Cylinder 2
X-ray source voltage	kV	90	205
X-ray source current	μA	45	130
Copper filter thickness	mm	-	3
Number of projections	-	1000	1000
Source detector distance	mm	984.27	984.27
Source object distance	mm	339.51	339.51
Geometrical magnification	-	2.90	2.90
Detector size	pixel × pixel	3192 × 2296	3192 × 2296
Pixel size	μm	127	127

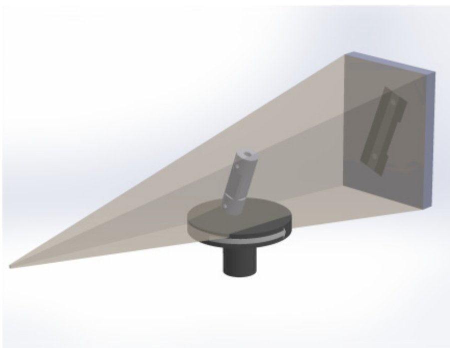

Fig. 6 Display of object during scanning process

3. Results and discussion

In order to estimate capabilities of industrial CT in the field of dimensional measurement of products with close tolerances, measurements of inspected samples were conducted using the same measurement approach in CMM and CT measurements. The approach considered fitting simple geometry objects such as planes and cylinders using the Gaussian method, where all observations were focused on observing relations between different combinations of those two simple objects. What was observed were dimensions of outer and inner cylinders, distances between two planes, distance between two cylinders and distance between cylinder and plane, as shown in Table 3. All measurements were conducted in good thermal conditions ($t = 20\,°C \pm 1\,°C$).

Scaling correction of CT data sets has been performed using the calibrated ball bar where distance between two ruby spheres on carbon rod was used to correct the nominal voxel size.

CT measurements were repeated five times and results are shown in Table 4 as the arithmetic mean of measured results $\bar{x}$ with given standard deviation s for each measurand and for each cylinder.

Table 3 Measurement strategies used for the volumetric data evaluation

Measurand	Symbol	Measurement strategy
Cylinder length	h	Plane-plane
Outer diameter	D	Cylinder
Inner diameter	d	Cylinder
Distance between two holes	l_1	Cylinder-cylinder
Distance between plane and centre of one hole	l_2	Plane-cylinder
Distance between planes	l_3	Plane-plane

Table 4 CT measurement results with given standard deviation for both cylinders

	Cylinder 1		Cylinder 2	
	$\bar{x}$ mm	s, mm	$\bar{x}$, mm	s, mm
D	29.966	0.006	30.011	0.003
d	06.019	0.002	06.013	0.002
h	89.951	0.020	90.043	0.006
l_1	65.032	0.002	64.975	0.001
l_2	09.957	0.024	10.001	0.032
l_3	24.012	0.015	23.942	0.017

Fig. 7 presents deviations between results obtained by CT and CMM measurements. Deviations are expressed as differences between CT measurements and reference CMM measurements and are given in micrometers for each observed measurand and for each cylinder.

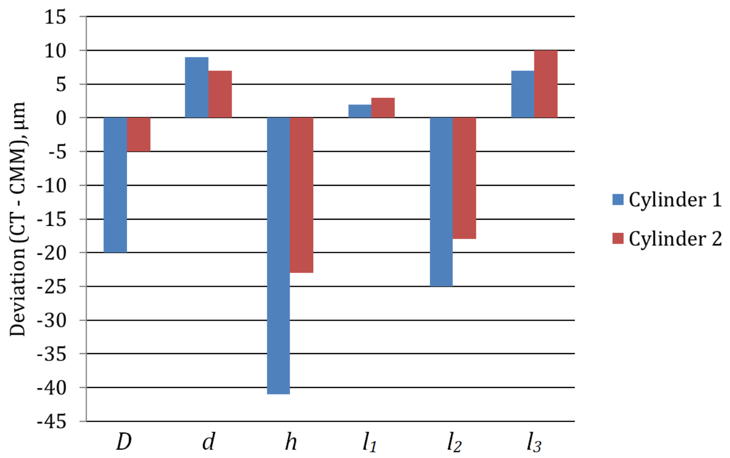

Fig. 7 Deviation between CT and CMM results for cylinder 1 and cylinder 2

First, the diameters of simple fitted features were observed: cylinders. The outer diameters of inspected parts were observed as outer cylinders, where the obtained results were in both cases lower than reference values, meaning that all deviations were negative. Slightly better results, in terms of deviation from reference values, were obtained in cases when outer diameter of aluminium cylinder was inspected. Measurements of inner diameter of hole d, showed similar behaviour in cases when measuring inner diameter of the two cylinders. Deviations equalled approximately 10 micrometers, where amounts larger than reference values were obtained with

CT, which resulted in positive deviations. Similar results were also obtained in [8] where outer and inner diameters of observed stainless steel cylinder were inspected. Obtained deviations were in range from (–0.008 to 0.014) micrometers where also different directions of deviations have been noticed when measuring outer and inner diameters. Different directions of deviations when measuring inner, as opposed to outer diameters, can be explained through threshold value. If chosen threshold value was greater than the optimum value, outer diameters would be smaller than actual size i.e. inner diameters would be greater than real value and vice versa [19].

Secondly, distances between different combinations of simple fitted objects were observed. When observing cylinder length h, defined as distance between border objects' planes, the biggest deviation from reference value was obtained. Such result can be explained by the measurement approach where length is observed as distance between two planes parallel to X-ray source. In that case, noise appears on the borders of inspected part and in this case, presence of noise on border planes affects object length. In both cases CT results were lower than reference values which resulted in negative deviations. Furthermore, such negative deviations in cylinder length also can be attributed to the chosen threshold value.

In the case when distance between two holes was observed, characteristic l_1, small or even no deviation between obtained results was expected. No matter what the inner diameter amounts (which depends on determined threshold), the distance between two holes remains the same. This is why measurement of the distance between two holes (or two spheres) is often used for scale error correction [20]. The expectations were proved. In both cases obtained deviations were the lowest in comparison to other results.

When analyzing results of distance between a plane and a hole, marked with l_2, similar behaviour was observed as in case of cylinder length h, despite the fact that different relations between simple objects were observed. Considering the fact that l_2 is defined as the length between border plane and an inner hole (where border noise, which has a great impact on results, appeared) higher deviations in results were expected. Also, when observing length h, higher deviation was obtained in case of cylinder 1. Therefore, higher deviations were again expected in case of cylinder 1. A lot more noise was present in measuring polymer cylinder, which implies impact of object material on measurement results.

One more measurand was observed, distance (l_3) between two planes perpendicular to planes that define object's overall length. Relying on results obtained in the case when h was observed, which was also defined as distance between two planes, the same behaviour of results as in case of cylinder length was expected. Obtained deviations were positive in both cases, which is contrary to expectations. Similar behaviour was also observed in [10] where two lengths (L_T and L_F) on a dose engine made from brass were measured. The measurement approach was held in the same way i.e. lengths were determined as distances between two parallel planes. Observed distances were perpendicular to each other, same as here with distances h and l_3. Explanation can be seen in position of observed characteristic, related to beam radiation.

Furthermore, the standard deviations and arithmetic means of the two samples were compared using the F test and the T test. By applying the F test it was determined that standard deviations do not significantly differ ($p > 0.05$) except in case of measuring the cylinder length. Reason for that can be found in measurement approach. In total, five scans of each cylinder were made. Cylinder length was defined as distance between two planes which were fitted to data by random selection of points. Results are given in Table 5. Furthermore, T test was conducted and results are given in Table 6.

Table 5 Results of F test for all measurands

Measurand	p-value
Outer diameter, D	$p = 0.208$
Inner diameter, d	$p = 1$
Cylinder length, h	$p = 0.039$
Distance between two holes, l_1	$p = 0.208$
Distance between plane and hole, l_2	$p = 0.591$
Distance between two planes, l_3	$p = 0.814$

Table 6 Results of conducted T test

Measurand	p-value
Outer diameter, D	$p = 0.001$
Inner diameter, d	$p = 0.153$
Cylinder length, h	$p = 0.126$
Distance between two holes, l_1	$p = 0.347$
Distance between plane and hole, l_2	$p = 0.706$
Distance between two planes, l_3	$p = 0.775$

Because the p-values are larger than reasonable choice of $\alpha = 0.05$, there is no significant evidence to reject the null-hypothesis stating that arithmetic means are equal. In the case of measuring outer diameters, the p-value is less than alpha risk, meaning there is a significant difference between arithmetical means. In majority of cases, results of equal characteristics obtained from different materials are comparable. It can be concluded that deviations from referent values of all characteristics, except cylinder length obtained at cylinder 1, are approximately ± 25 µm. Pooled experimental standard deviation s_p was estimated and equals 16 µm. Higher deviations could be explained by the fact that the measurements were performed at an industrial CT for general applications. Significantly better results can be achieved using a metrological CT device.

4. Conclusions

Computed tomography has numerous advantages, which makes it very desirable for dimensional measurements and quality control in wide range of industries. However, lack of metrological traceability and accepted procedures still prevents its wider use. In order to define capabilities of industrial computed tomography in the field of dimensional measurements two objects with the same geometry, made from different materials, were measured. Selection of materials and dimensions as well as objects design was conducted in order to cover interesting and frequently used materials in industries.

Measurements of six dimensional characteristics were conducted using the same measurement approach in both the CMM and CT measurements. Results were observed and presented as deviations from CMM results, which were considered to be reference values. Obtained results are in agreement with previous researches. Deviations from referent values of all characteristics, except cylinder length obtained at cylinder 1, are approximately ± 25 µm. Pooled experimental standard deviation s_p was estimated and is equal to 16 µm. Higher deviations could be explained by the fact that the measurements were performed at an industrial CT for general applications. Much better results can be achieved by using a metrological CT device. Also, the standard deviations and arithmetic means of the two samples were compared using the F test and the T test. By applying the F test it was determined that standard deviations do not significantly differ ($p > 0.05$) except when measuring the cylinder length. Reason for that can be found in measurement approach. By applying the T test it was determined that arithmetic means do not significantly differ ($p > 0.05$) except in case when measuring the outer diameters. Explanation of obtained results can be given through selection of threshold value.

Considering the fact that a CT device offers simultaneous examination of more properties (dimensional characteristics, material analysis), growing application and implementation of CT systems in industry is expected. However, the measurement uncertainty of results needs to be assessed, so the further researches should be focused on its evaluation. Considering the requirements, it is advised that further researches are undertaken using Monte Carlo simulations. A bigger emphasis should be placed on identifying and eliminating systematic errors, as well as on developing measurement procedures with the aim of minimizing operator influence.

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References

[1] Kruth, J.P., Bartscher, M., Carmignato, S., Schmitt, R., De Chiffre, L., Weckenmann, A., (2011). Computed tomography for dimensional metrology, *CIRP Annals – Manufacturing Technology*, Vol. 60, No. 2, 821-842, doi: 10.1016/j.cirp.2011.05.006.

[2] Klobucar, R., Acko, B. (2016). Experimental evaluation of ball bar standard thermal properties by simulating real shop floor conditions, *International Journal of Simulation Modelling*, Vol. 15, No. 3, 511-521, doi: 10.2507/IJSIMM15(3)10.356.

[3] Müller, P., Cantatore, A., Andreasen, J.L., Hiller, J., De Chiffre, L. (2013). Computed tomography as a tool for tolerance verification of industrial parts, *Procedia CIRP*, Vol. 10, 125-132, doi: 10.1016/j.procir.2013.08.022.

[4] De Chiffre, L., Carmignato, S., Kruth, J.-P., Schmitt, R., Weckenmann, A. (2014). Industrial application of computed tomography, *CIRP Annals – Manufacturing Technology*, Vol. 63, No. 2, 655-677, doi: 10.1016/j.cirp.2014.05.011.

[5] Horvatić Novak, A., Runje, B. (2016). Dimensional measurement with usage of computed tomography method, In: *Proceedings of 6th International Conference Mechanical Technologies and Structural Materials*, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia, 51-54.

[6] Horvatić Novak, A., Runje, B., Butković, D. (2016). Influence of geometrical magnification on computed tomography dimensional measurements, In: *Annals of DAAAM International for 2016, Collection of working papers for 27th DAAAM International Symposium*, DAAAM International Vienna, Vienna, 615-623.

[7] Welkenhuyzen, F., Kiekens, K., Pierlet, M., Dewulf, W., Bleys, P., Kruth, J.-P., Voet, A. (2009). Industrial computer tomography for dimensional metrology: Overview of influence factors and improvement strategies, In: *Proceedings of the 4th International Conference on Optical Measurement Techniques for Structures and Systems: Optimess2009*, Antwerp, Belgium, 401-410.

[8] Hiller, J., Reindl, L.M. (2012). A computer simulation platform for the estimation of measurement uncertainties in dimensional X-ray computed tomography, *Measurement,* Vol. 45, No. 8, 2166-2182, doi: 10.1016/j.measurement.2012.05.030.

[9] Acko, B., Sluban, B., Tasič, B., Brezovnik, S. (2014). Performance metrics for testing statistical calculations in interlaboratory comparison, *Advances in Production Engineering & Management*, Vol. 9, No. 1, 44-52, doi: 10.14743/apem2014.1.175.

[10] Müller, P., Hiller, J., Dai, Y., Andreasen, J.L., Hansen, H.N., De Chiffre, L. (2014). Estimation of measurement uncertainties in X-ray computed tomography metrology using the substitution method, *CIRP Journal of Manufacturing Science and Technology*, Vol. 7, No. 3, 222-232, doi: 10.1016/j.cirpj.2014.04.002.

[11] BIMP (2009). JCGM 100:2008 – Evaluation of measurement data – Guide to the expression of uncertainty in measurement, from *http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf*, accessed February 17, 2017.

[12] BIMP (2009). JCGM 101:2008 – Evaluation of measurement data – Supplement 1 to the "Guide to the expression of uncertainty in measurement" – Propagation of distributions using a Monte Carlo method, from *http://www.bipm.org/utils/common/documents/jcgm/JCGM_101_2008_E.pdf*, accessed February 17, 2017.

[13] ISO 15530-3:2011 (2011). *Geometrical product specifications (GPS) -- Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement*, ISO copyright office, Geneva, from https://www.iso.org/standard/53627.html, accessed March 27, 2017.

[14] NPL: X-ray computed tomography, from *http://www.npl.co.uk/science-technology/dimensional/x-ray-computed-tomography*, accessed May 7, 2017.

[15] Acko, B., McCarthy M., Haertig, F., Buchmeister, B. (2012). Standards for testing freeform measurement capability of optical and tactile coordinate measuring machines, *Measurement Science and Technology*, Vol. 23, No. 9, 1-13, doi: 10.1088/0957-0233/23/9/094013.

[16] Tasic, T., Acko, B. (2011). Integration of a laser interferometer and a CMM into a measurement system for measuring internal dimensions, *Measurement*, Vol. 44, No. 2, 426-433, doi: 10.1016/j.measurement.2010.11.002.

[17] Nikon metrology – CT scanners specifications, from *http://www.nikonmetrology.com/en_EU/Products/X-ray-and-CT-Inspection/Computed-Tomography/XT-H-225-Industrial-CT-Scanning/(specifications)*, accessed November 8, 2016.

[18] Schmitt, R., Niggemann, C. (2010). Uncertainty in measurement for x-ray-computed tomography using calibrated work pieces, *Measurement Science and Technology,* Vol. 21, No. 5, doi: 10.1088/0957-0233/21/5/054008.

[19] Cantatore, A., Müller, P. (2011). *Introduction to computed tomography*, DTU Mechanical Engineering, Kgs.Lyngby, Denmark.

[20] Müller, P. (2010). *Use of reference objects for correction of measuring errors in X-ray computed tomography,* DTU Mechanical Engineering, Kgs.Lyngby, Denmark.