euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023
www.euspen.eu

The investigation of the combination of the object orientation to evaluate the measurement uncertainty of the X-ray CT using the analysis of variance

Kazuya Matsuzaki[1)], Mari Watanabe[1)], Osamu Sato[1)]

[1] *Research Institute for Engineering Measurement, National Metrology Institute of Japan (NMIJ), National institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan*

kazya.36.matsuzaki@aist.go.jp

Abstract
X-ray computed tomography (X-ray CT) is the only practical technology that enables the measuring of internal geometrical features, therefore, it has been widely used in the manufacturing industry. This application is a kind of coordinate metrology which has the advantage of the capability to measure various measurands such as dimensions and forms related to geometrical tolerance. The task-specific measurement uncertainty is required to ensure the traceability of the measurement results. However, the evaluation method for that has not been established in the X-ray CT measurement except for the comparison measurement using a calibrated masterpiece. In recent years, the development of measurement uncertainty evaluation method using analysis of variance has been progressive, and reported the example of an application for the Cartesian coordinate measuring machine (CMM). This method is expected to be applied to evaluate the uncertainty of X-ray CT measurement result without pre-calibrated masterpieces. The essential technique of this method is the randomization of the dominant systematic error factors included in the measurement results in multiple measurement conditions. The discussion about the combination of the object orientation to randomize the systematic error factors is necessary for applying the method to the X-ray CT. In this research, we studied the optimal combination of the object orientations in which the dominant systematic error factors are randomized to apply the uncertainty evaluation method using the analysis of variance. First, we obtained 10 orientations measurement data by rotating 90° around each of the X, Y, and Z axes using the actual machine.

Keywords: X-ray CT, task-specific measurement uncertainty, coordinate metrology, analysis of variance

1. Introduction

Three-dimensional coordinate measurement technologies are beneficial in the production processes such as quality inspection in the manufacturing field. X-ray computed tomography (X-ray CT) is a kind of those technologies that has attracted attention from the industry in recent years. This is because of the advantages of the capability to measure inner features and the capability to obtain the whole information of the workpiece to be measured as digital data in a short time. These advantages have good compatibility with new technology fields such as digital transformation (DX) and additive manufacturing (AM) and their importance is increasing.

IATF16949 [1] and other standards require ensuring the SI traceability of the measurement instruments to certify the measurement result [2]. To meet this requirement, a calibrated reference standard to be used for evaluating the performance of the instrument is needed. It is useful that the reference standard can be calibrated using X-ray CT because some reference standards for X-ray CT are difficult to be measured by different types of measuring systems such as CMM. To realize the calibration using X-ray CT, it is necessary to establish a method to evaluate the task-specific measurement uncertainty of X-ray CT measurement results. Previous studies such as Muller et al. [4] reported the uncertainty evaluation results using the substitution method standardized as an ISO 15530-3 [5]. On the contrary, a method of evaluating measurement uncertainty using analysis of variance (ANOVA) has been developed in recent years [6].

In this paper, a difference in the X-ray CT measurement result in the different workpiece orientations is investigated to discuss the combination of the orientations suitable to the method.

2. Uncertainty calculation method using ANOVA

This study introduces a method of evaluating the task-specific uncertainty using ANOVA, which was developed by the EURAMET 17NRM03 EUCoM project in the EU and the METI project in Japan. The previous research [7] reported the uncertainty evaluation method by applying the above-mentioned method to CMM measurement. Currently, it is under the standardization process as ISO/TS 15530-2.

In this method, the measurement uncertainty is assumed to be a composition of random and systematic errors. The dominant uncertainty factors are randomized in multiple measurement results with different conditions and evaluated as modules. The measurement uncertainty is calculated by combining the modularised components that are evaluated by performing ANOVA on the measurement results obtained under multiple measurement conditions and systematic errors that are not randomized in the multiple measurements and are evaluated separately.

To apply this method to X-ray CT, it is important to set measurement conditions that can randomize error factors. Measurement cost increases depending on the number of measurement conditions, however, a smaller number of conditions increases the risk of underestimation of the uncertainty.

3. Experimental settings and results

A verification experiment for the applicability of the above ANOVA method to X-ray CT was performed in this study. The center-to-center distances of spheres were measured with multiple workpiece orientations using the Dimensional X-ray CT system XDimensus300s (produced by Shimadzu Co.). The workpiece to be measured is a new material standard developed by AIST, which consists of eight silicon nitride spheres enclosed in a resin cylinder.

At first, three continuous measurements were performed under identical conditions for repeatability evaluation. Next, measurements were performed in a total of 10 workpiece orientations rotating every 90 degrees around three orthogonal axes. The workpiece orientations are summarized in Figure 1.

Measurement results are shown in Figure 2. The plotted deviation indicates the difference from the average of 10 results of each length. The standard deviation due to the difference in workpiece orientations was 1.10 µm, which was three times larger than repeatability which was 0.36 µm. In addition, it was confirmed that the variation caused by rotating around the Z-axis is smaller than that caused by rotating around the X- and Y-axes.

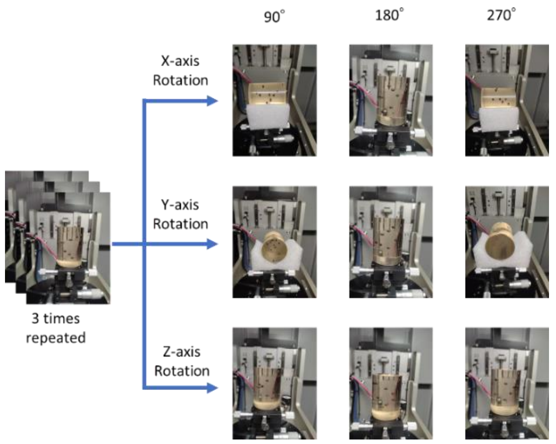

Figure 1 Overview of obtained dataset.

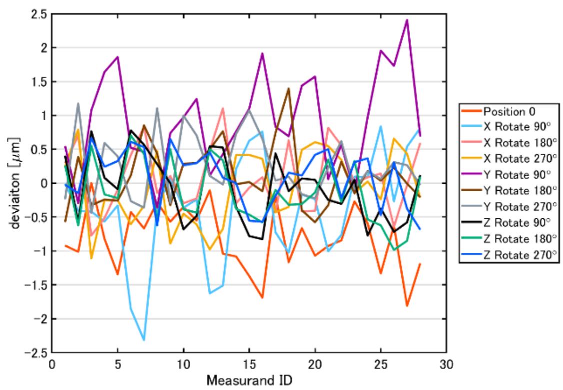

Figure 2. Length measurement results in various workpiece orientations.

In this case, the task-specific uncertainty u_{result} of the center-to-center distance of spheres can be modelized as the following equation.

$$u_{result} = \sqrt{E_{scale}^2 + u_{Scale}^2 + u_{temp}^2 + u_{CTE}^2 + u_{rep}^2 + u_{geo}^2 + u_{geo\times dist}^2}$$

Uncertainty of measurement result can be calculated by combining the above factors as summarized in table 1. An expanded uncertainty (coverage factor: k = 2) was obtained as 3.0 µm for the maximum length of 34.78 mm measured in this experiment.

Table 1. Uncertainty budget using ANOVA method.

Contribution factor	Uncertainty [µm]
E_{scale}: Scale error of reconstructed volume	1.264
u_{scale}: Uncertainty of scale error	0.210
u_{temp}: Variation of temperature	0.072
u_{CTE}: Uncertainty of CTE of workpiece	0.000
u_{rep}: Repeatability	0.363
u_{geo}: Systematic error of the CT system	0.427
$u_{geo\times dist}$: Interaction between the systematic error of CT system and the distribution of the measurand	0.575
Combined standard uncertainty	1.51
Expanded Uncertainty (k=2)	3.02

4. Summary

The effect of the workpiece orientation was investigated to apply the uncertainty evaluation method by ANOVA to X-ray CT measurement. As a result of measurement with rotating each 90 degrees around three orthogonal axes, the difference between vertical and horizontal orientations showed largest difference. There are two possible expanding directions of this research. One is the investigation of optimal combination of the workpiece orientations by actual measurement and software simulation. The second is development of material standard which has small uncertainty factors derived from the standard itself.

Acknowledgment

This work was supported by Mitutoyo Association for Science and Technology (MAST).

References

[1] IATF16949 Quality management system requirements for automotive production and relevant service parts organizations 2016.

[2] Ferrucci M, Ametova E. Charting the course towards dimensional measurement traceability by x-ray computed tomography. Meas Sci Technol 2021;**32**:092001. https://doi.org/10.1088/1361-6501/abf058.

[3] Villarraga-Gómez H, Lee C, Smith ST. Dimensional metrology with X-ray CT: A comparison with CMM measurements on internal features and compliant structures. Precision Engineering 2018;51:291–307. https://doi.org/10.1016/j.precisioneng.2017.08.021.

[4] Müller P, Hiller J, Dai Y, Andreasen JL, Hansen HN, Chiffre L. Estimation of measurement uncertainties in X-ray computed tomography metrology using the substitution method. CIRP Journal of Manufacturing Science and Technology 2014;**7**:222–32. https://doi.org/10.1016/j.cirpj.2014.04.002.

[5] ISO 15530-3 Geometrical product specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement — Part 3: Use of calibrated workpieces or measurement standards 2011.

[6] Sato O, Takatsuji T, Balsamo A. Practical experimental design of task-specific uncertainty evaluation for coordinate metrology. Advanced Mathematical and Computational Tools in Metrology and Testing XII, vol. **90**, 2022, p. 381–389. https://doi.org/10.1142/9789811242380_0023.

[7] Sato O, Takatsuji T, Miura Y, Nakanishi S. GD&T task specific measurement uncertainty evaluation for manufacturing floor. Measurement: Sensors 2021;**18**:100141. https://doi.org/10.1016/j.measen.2021.100141.