

# BRIEF MACHINE CHECKING FOR COORDINATE MEASURING SYSTEM USING X-RAY COMPUTED TOMOGRAPHY

Osamu SATO\*, Hiroyuki FUJIMOTO\*, Sonko OSAWA\*, Makoto ABE\* and Toshiyuki TAKATSUJI\*

\*National Metrology Institute of Japan, AIST Tsukuba Central 3, Umezono 1-1-1, Tsukuba, Ibaraki 305-8563, JAPAN, osm-satou@aist.go.jp

## Abstract:(250 Words)

Form and dimensional measurements using X-ray Computed Tomography (X-ray CT) are useful on product development, reverse engineering, production control and quality certification because X-ray CT system can get three dimensional volumetric data of the full body of the target object at one time. Generally, three dimensional coordinate measuring systems (CMSs), in which X-ray CTs are also included, have measurement space distorted by the kinematic and other factors. Therefore, the deformation of the measurement space should be compensated for precise dimensional measurement. Moreover, the compensation function should be checked occasionally. In case of a widely-used coordinate measuring machine (CMM), the mobile frame of the machine is stable over a long period. Therefore, it is not necessary to check whether the compensation function on the CMM works well or not so frequently. In comparison with a CMM, the mobile frame of an X-ray CT is less stable. Thus, the space deformation compensation function on X-ray CTs should be checked at shorter interval than that on CMMs in order to perform precise dimensional measurement using X-ray CTs. In this research, a brief machine checking method for an X-ray CT is proposed. Through the repeating checking, the assessment of the long-term stability of the mobile frame of an X-ray CT is demonstrated.

**Keywords:** X-ray CT, Coordinate measuring systems, Dimensional measurement, Interim check

## 1. INTRODUCTION

Coordinate measuring systems (CMSs) are useful for geometrical features evaluation on the products in industry. Since 1960s, Cartesian coordinate measuring machines (CMMs) equipped with tactile probing systems have been widely used for the geometrical measurements. Recently, the use of other types of CMSs is increasing because of the systems' advantages over CMMs, e.g. high measurement speed or high density of sampling. Especially, X-ray computed tomography systems (X-ray CTs) expand the application because X-ray CTs can perform the non-destructive measure the features of the products whose surfaces are not visible or approachable from the outside of the objects.

Using CMS, the dimensions or form of the products are measured precisely for the purpose of product development, reverse engineering, production control, quality certification and so on. To keep the measurement accuracy of CMS in a satisfactory level, the CMS should be verified its measure-

ment performance through the calibration or interim check process [1]. However the mobile frame of CMMs installed into the measuring room circumstances, the operators of the CMMs execute the interim check for the measurement quality managements. Since the stability of the mobile frame of X-ray CT is inferior to CMM's, the measurement accuracy of X-ray CT should be monitored more carefully.

In case of CMMs, several manner of the interim check have been proposed [2–4], and some devices for the check are commercialized. In contrast, the verification methods for X-ray CTs are under development [5]. The difficulty of the interim check procedure development for X-ray CT is caused by the complex error factors of the system. Here note that CMMs also have complex kinematics systems, however, some commercialized interim checking methods for CMMs simplify the error factors of the measurement as the deformation of the measurement volume according to the affine transformation. Similarly, the brief accuracy checking manner for X-ray CT can be developed using simple coordinate transformation procedure.

In this paper, an interim checking method for X-ray CT is proposed. Through the verifications of a X-ray CT with the proposed manner, the stability assessment of the X-ray CT is demonstrated.

## 2. BRIEF CHECK FOR CMS

Coordinate system on an actual CMS is deformed from the ideal orthonormal coordinate system. The deformation of the coordinate system reflects the corresponding distortion of the measurement frame of the CMS. Usually, the coordinate deformation is expressed using the limited numbers of parameters. For example, the deformation of the coordinate system of an Cartesian CMM is formulated using 21 kinematic parameters (Fig. 1 (a)).

When performing the complete performance test of the CMM, the 21 kinematic parameters should be calibrated. Since the complete performance evaluation takes long time, brief performance check is done more frequently to control the measuring performance of the CMM. On the brief performance check, smaller number of parameters which are the dominant error contributors are estimated. In the case of established brief checks for CMMs, only six parameters are verified; scale errors along X-, Y- and Z-axes and orthogonal errors between respective the axes.

The brief check means the identification of the linear transformation from the unit cube to the corresponding parallelepiped (Fig. 1 (b) and Eq. (1)), where  $p_{calib}$  means the cali-

brated coordinates of the artefact and  $p_{meas.}$  means the coordinates measured on the deformed coordinate system.  $A$  is  $3 \times 3$  matrix. The three scale errors and the three orthogonal errors are computed from the matrix.

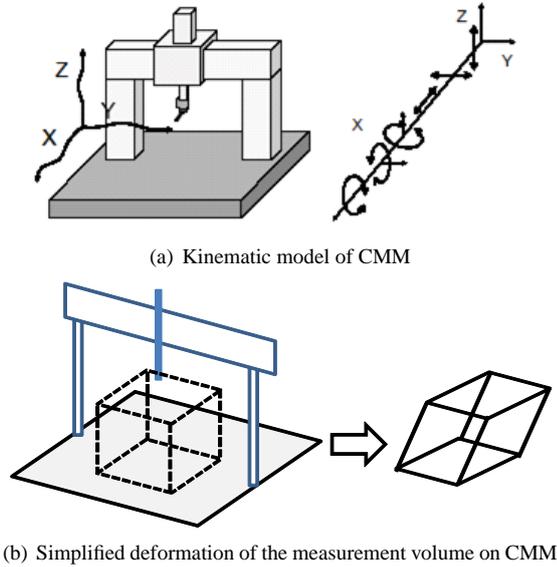


Fig. 1: Scheme of the brief CMM checking

$$p_{meas.} = Ap_{calib.} \quad (1)$$

Figure 2 shows the artefacts of the gauges for the brief check of CMM. At least twelve coordinates should be measured to identify the three scale errors and the three orthogonal errors because the position and orientation of the artefact in the machine coordinate system on the CMM should be identified simultaneously. Therefore, total number of the coordinates to be measured is not less than twelve. The artefact shown in Fig. 2 (a) have four spheres and the respective centres of the spheres are calibrated. The artefact satisfies the minimum number of components for the brief check.

Generally, it takes longer time when the number of the measured elements is increased for the CMM brief check because the measurement time is proportion to the total number of the measurement when using CMM. On the other hand, the robustness of the result of the check is improved using the larger number of the elements to be measured. The artefact shown in Fig. 2 (b) is another artefact for CMM brief check. Eight spheres are installed on the artefact for measurement redundancy. The CMM test using the artefact can be completed within 10 minutes.

### 3. BRIEF CHECK FOR X-RAY CT

In the case of X-ray CT, the deformation of the coordinate system related to the machine is different from that of CMM, however, the basic concept of the brief check is similar. When the architecture of CMS is different from that of Cartesian CMM, the kinematic models and parameters expressing the system are different from those of the Cartesian CMM, the

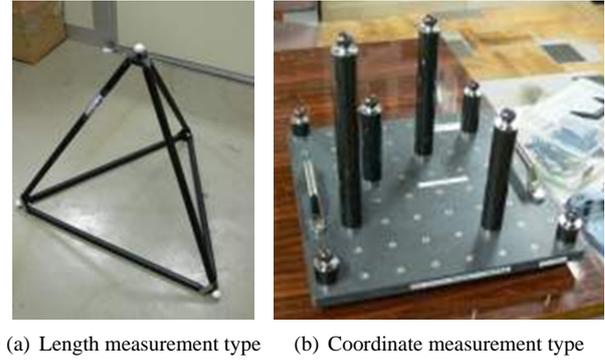
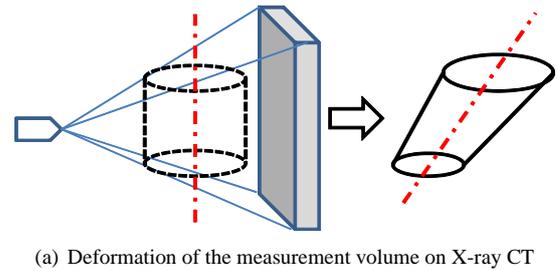


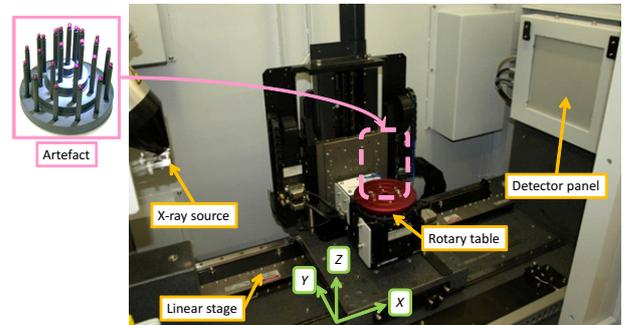
Fig. 2: Artefacts for brief CMM checking

dominant error contributors are the three scale errors and three orthogonal errors.

The deformation of the coordinate system on X-ray CT is expressed as the transformation from the unit cylinder to the truncated oblique cone (Fig. 3 (a)). To identify the transform matrix, an artefact is measured using the X-ray CT (Fig. 3 (b)).



(a) Deformation of the measurement volume on X-ray CT



(b) Artefact and X-ray CT system for verification

Fig. 3: Brief check for X-ray CT

The transform matrix of the coordinates on X-ray CT is calculated from Eq. (2):

$$P_{i,meas.} = T_i P_{calib.}, \quad (2)$$

where,  $i$  is the ID of the brief check,  $P_{i,meas.}$  is the measurement result in the  $i$ -th trial and  $P_{calib.}$  is the calibrated value of the artefact. The transform matrix  $T_i$  is calculated as follows:

$$T_i = P_{i,meas.} {}^t P_{calib.} (P_{calib.} {}^t P_{calib.})^{-1}, \quad (3)$$

where,

$$P_{calib.} = \begin{bmatrix} x_{1,calib.} & \cdots & x_{n,calib.} \\ y_{1,calib.} & \cdots & y_{n,calib.} \\ z_{1,calib.} & \cdots & z_{n,calib.} \\ 1 & \cdots & 1 \end{bmatrix}, \text{ and} \quad (4)$$

$$P_{i,meas.} = \begin{bmatrix} x_{i,1,meas.} & \cdots & x_{i,n,meas.} \\ y_{i,1,meas.} & \cdots & y_{i,n,meas.} \\ z_{i,1,meas.} & \cdots & z_{i,n,meas.} \\ 1 & \cdots & 1 \end{bmatrix}. \quad (5)$$

In each verification, the transpose matrix;

$$T_i = \begin{bmatrix} a & b & c & | & x \\ k & l & m & | & y \\ p & q & r & | & z \\ s & t & u & | & 1 \end{bmatrix} \quad (6)$$

is identified.

In contrast to CMM, X-ray CT measurement takes same time to measure the artefact on which larger number of elements are installed. That is because the all elements are measured simultaneously using X-ray CT. Therefore, it is efficient to use redundancy artefact for the brief check of X-ray CT.

#### 4. EXPERIMENT

A series of brief check was performed for the X-ray CT system. The target system, the measurement conditions and artefact are shown in Tab. 1.

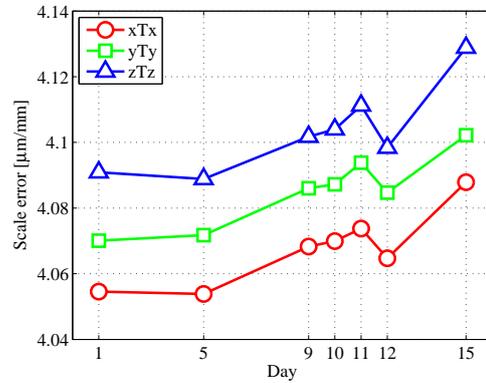
Tab. 1: Measurement condition

System	SIMADZU inspeXio SMX-225CTS
X-ray energy	160 kV
Currency	50 $\mu$ A
Focus size	4 $\mu$ m
Voxel size	121.2 $\mu$ m/voxel
Number of view	1200
Averaging per view	7
Metal filter	None
Total time of measurement	1700 sec/test
Temperature	20 $^{\circ}$ C $\pm$ 1 $^{\circ}$ C
Size of the artefact	$\phi$ 104 mm $\times$ h 45 mm
Material of the artefact	Low CTE ceramics
CTE of the artefact	$0.0 \times 10^{-6}$ /K $\pm 0.5 \times 10^{-8}$ /K
Number of installed sphere	25
Diameter of installed sphere	5 mm

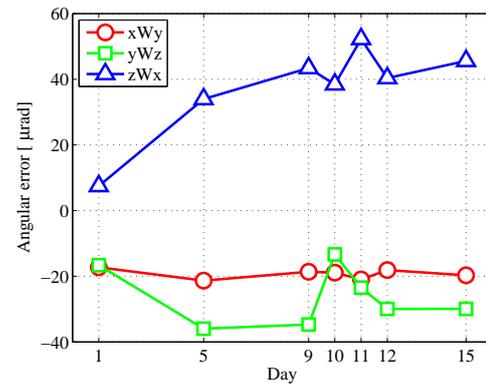
In the brief test, the artefact shown in Fig. 3 (b) was measured once per trial. From the reconstructed CT data, the interface between air and the installed spheres was extracted using the threshold value evaluated by the measuring software (VG 2.2) automatically. The coordinates of the respective centres of the spheres were calculated on the same software. The transform matrix was computed from the measurement data of the artefact using the X-ray CT and that measured using a high precision CMM (Panasonic UA3P).

The scale errors and orthogonal errors are evaluated from the transform matrix. Figure 4 shows the results of the brief

check. The variation of the six errors are detected through the test. In the test, the X-ray CT system was verified seven times in two weeks. In the test term, the system had been also used for other measurements tasks. Thus the result of the test shows the stability of the system.



(a) Scale errors



(b) Orthogonal errors

Fig. 4: Results of brief check

Figure 4 (a) shows that the scale errors change in the test term. It means that the magnification error of the system changes in the term. Moreover, the proportion between respective scale errors are not constant. It means that the proportion of the voxel derived from the system changes. Figure 4 (b) shows the change of orthogonal error between X- and Z-axes is larger than others. It means that the pitching error of the linear actuator installed along X- axis of the system is large.

#### 5. SUMMARY

In this paper, a brief check for X-ray CT is proposed. Through the verifications of a X-ray CT with the proposed manner, the stability assessment of the X-ray CT is demonstrated. In further study, the measurement conditions of the brief test will be optimized and the total time of the test shall be shorten for the industrial applications.

## REFERENCES

- [1] ISO 10360-2:2009, Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 2: CMMs used for measuring linear dimensions.
- [2] A. Weckenmann and J. Lorz, “Monitoring coordinate measuring machines by calibrated parts”, *Journal of Physics: Conference Series*, vol.13, pp. 190-193, 2005.
- [3] V. Nardelli and G. Donatelli, “A simple solution to interim check of coordinate measuring machines”, *Proc. XVIII IMEKO WORLD CONGRESS*, Rio de Janeiro, Brazil, Sep. 2006.
- [4] R. Furutani, T. Itabashi and M. Ozaki, “Comparison of daily check artefacts of CMM”, *Proc. 11th International Symposium on Measurement and Quality Control 2013*, Cracow-Kielce, Poland, Sep. 2013.
- [5] K. Kiekens, F. Welkenhuyzen, T. Tan, P. Bleys, A. Voet, W. Dewulf and J. P. Kruth, “A test object for calibration and accuracy assessment in X-ray CT metrology”, *Proc. 10th International Symposium on Measurement and Quality Control 2010*, Osaka, Japan, Sep. 2010.