CIRP Journal of Manufacturing Science and Technology 7 (2014) 222–232

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Estimation of measurement uncertainties in X-ray computed tomography metrology using the substitution method

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ARTICLE INFO

Article history:
Available online 24 May 2014

Keywords:
X-ray computed tomography
CT
Measurement uncertainty
ISO 15530-3
Substitution method
Calibrated workpieces
Master piece
Reference objects
CT ball plate

ABSTRACT

This paper presents the application of the substitution method for the estimation of measurement uncertainties using calibrated workpieces in X-ray computed tomography (CT) metrology. We have shown that this, well accepted method for uncertainty estimation using tactile coordinate measuring machines, can be applied to dimensional CT measurements. The method is based on repeated measurements carried out on a calibrated master piece. The master piece is a component of a dose engine from an insulin pen. Measurement uncertainties estimated from the repeated measurements of the master piece were transferred on to additionally scanned uncalibrated workpieces which provided the necessary link for achieving traceable measurements.

Introduction

In today's industrial world, the focus on precision and accuracy in production engineering is of main importance. Industrial components are more and more complex and the demands for quality control and quality assurance increase. Therefore, new technologies are being developed in order to fulfill the customer's needs and requirements. X-ray computed tomography (CT), known for its broad use in medical applications since more than 30 years, has been rapidly developed also for industrial use. Using CT, a complete three-dimensional image of the scanned part can be produced in a relatively short time, which is achieved by penetrating the object from multiple angles using X-ray radiation in connection with 3D image reconstruction. Since CT data contain complete volumetric information about the measured part, it is possible, by determination of the object's surface from volume data to evaluate spatial coordinates of the measured body. This means that CT can be used to perform dimensional and geometrical measurements similar to a, e.g., coordinate measuring machine (CMM). Due to the ability of X-rays to penetrate the inspected object, CT is capable to measure external and internal structures and to provide accurate dimensional and geometrical information with micrometer accuracy. This is also why CT offers new possibilities compared to traditional measuring techniques like tactile CMMs and optical measurement systems.

Because CT has been spread into the field of manufacturing metrology and coordinate metrology, an important parameter for quality control and reliability of the measurement process is the uncertainty of a measurement result. Measurement uncertainty is also an important parameter for comparability and acceptance of CT systems as a measuring instrument. ISO 10360-2 [1] and ISO 15530-3 [2] are two standards dealing with verification tests for tactile CMMs used for measuring sizes, and uncertainty estimation using calibrated workpieces, respectively. Because CT systems are quite new in their applications as coordinate measuring systems (CMSs), and, in general, due to the fact that there are many influence quantities in CT (an overview of influence factors in CT can be found in many research publications, e.g. [3–10]), internationally standardized procedures for metrological performance testing of CT systems and errors quantification are not

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http://dx.doi.org/10.1016/j.cirpj.2014.04.002
1755-5817/

available yet. Only draft of international or national guidelines are existing at present [11–16]. The attempt is to develop reference objects similar to those used in classical coordinate metrology, for identification of error sources and their subsequent compensation. Estimation of the measurement uncertainty is, however, very important due to traceability reasons. Traceability establishment requires estimation of task-specific uncertainty [17]. Achieving traceability in CT is of the major importance in industry, as otherwise CT cannot be considered as fully accepted measuring system. A few steps mentioned below are suggested to be followed leading to achievement of traceability in CT:

- Development of reference objects (e.g., for correction of systematic errors, task-specific measurement uncertainty assessment, etc.).
- Understanding of influence factors and assessing their impact on various measurands.
- Assessing methods for measurement uncertainty estimation.

The last mentioned key point in achieving traceability in CT is in more details described in the following. An overview of valid methods for the assessment of measurement uncertainty in CT is presented:

- Methods requiring a model equation – GUM method (JCGM 100:2008) [18], ISO 14253-2 [19].
- Empirical methods – use of calibrated workpieces or standards ISO 15530-3 [2], Use of multiple measurement strategies in calibration artifacts ISO/DTS 15530-2 [20].
- Computer simulation – Suppl. 1 to GUM (JCGM 101:2008) [21], VDI/VDE 2617-7 [22] and ISO/TS15530-4 [23].
- Combination of mentioned methods.

Description of methods for uncertainty estimation in CT can be found in literature, e.g. [3,24–26].

The objective of this paper is to document the applicability of the experimental approach using calibrated workpieces (ISO 15530-3) for uncertainty estimation of CT measurements in industrial environment. Because this approach requires a calibrated workpiece (master piece) similar in shape and material to the object under study, an industrial part from production – a component of dose engine – was used as the master piece in this work. Measurement uncertainties were determined task-specifically, providing the necessary link to traceable measurement.

The application of the substitution approach for uncertainty estimation for CT dimensional measurements was used, e.g., in [4,8,27–29]. Among the mentioned publications, only authors in [8] describe the use of ISO 15530-3 more specifically, they compared and combined simulations and experiments following the ISO standard, and concluded that a procedure using calibrated workpieces is most promising. The main benefit of this paper in regards to the mentioned publications is to provide a detailed assessment of individual uncertainty contributions for the estimation of measurement uncertainties using uncertainty budgets for both calibration and actual CT measurements of the part. Moreover, a direct link of the principles of this ISO standard between both CMM and CT measurements is highlighted. Furthermore, the magnitude of individual uncertainty components for both CMM and CT measurements is presented and discussed. A discussion regarding relevance of calculating bias and why this factor should not be included in the uncertainty budget but should rather be used as an indicator for accuracy assessment is held.

Due to the geometry complexity and the material of the component, this paper yields promising results and provides relevant discussion on the applicability of this method for uncertainty estimation of dimensional CT measurements in industrial practice.

The experimental method using the calibrated workpieces is described in more details in the following section.

Measurement uncertainty estimation using calibrated workpieces

The overall uncertainty may be evaluated through the substitution method, adapting the approach described in ISO 15530-3 for tactile CMMs. Since the substitution method is based on the use of calibrated workpieces, traceability of CT measurements can be established by comparison with traceable (calibration) results obtained from an accepted measuring system, e.g., tactile CMM [5], where measurements carried out on the CMM are set as reference [30]. This approach requires performing a series of repetitive measurements (20 measurements are recommended by the standard) under the same or similar conditions which are used in the production. Therefore, such a calibrated workpiece has to be as close as possible in size, geometry and material with respect to the real workpiece [25]. In practice, such a procedure is time consuming and might be very costly. Therefore, it is suggested in [8] to use a safety factor based on a Student-*t* distribution (with higher number of repeated measurements this factor becomes smaller). So, by multiplying the empirically obtained standard deviation with this factor it is ensured that the uncertainty contribution from procedure is not underestimated.

As discussed by many researchers, a critical point when applying the substitution method for uncertainty estimation is how to correctly treat systematic errors. The GUM suggests correcting the measurement results for any systematic effects. Recently, there has been a change in the assessment of the uncertainty calculation in ISO/TS 15530-3:2009 [31] in which a bias contribution b was considered, being squared under the square root together with other uncertainty contributors. However, in the latest version of the ISO 15530-3:2011 [2] the formula describing the assessment of the measurement uncertainty considers only a residual bias contribution u_b, and the bias itself is stated separately from uncertainty but together with the result, see Eq. (1). Eq. (2) then provides calculation of the bias. From the authors' point of view, the formulation according to the ISO 2011 version better captures the "problem" of CT. The absolute difference between CT and CMM is not negligible, due to the differences of tactile and CT coordinate measurements in general. These are, for example: number of sampling points, measuring strategy, mechanical filtering, measurement of internal structures, etc. (for more details see [6]). Therefore, it is more appropriate to assess the bias outside the measurement uncertainty rather than include it. The complete measurement result is given by

$$Y = \bar{y} - b \pm U, \tag{1}$$

where $\bar{y}$ is the expected value obtained by, e.g., CT, b is bias value and U is expanded uncertainty of measurement. The bias is given by

$$b = \bar{y} - x_{cal}, \tag{2}$$

where x_{cal} is the calibrated value obtained by, e.g., CMM. In our case, the bias represents a systematic deviation from reference.

Adapted substitution approach

The general concept of ISO 15530-3 was described in the previous section. We found it useful to document the applicability of this approach for uncertainty estimation of CT measurements. Since the ISO 15530-3 suggests carrying out at least 20