Means to Verify the Accuracy of CT Systems for Metrology Applications (In the Absence of Established International Standards)

Hubert Lettenbauer, Bernd Georgi, Daniel Weiß

Development CT Systems, Carl Zeiss Industrielle Meßtechnik GmbH
73447 Oberkochen, Germany; Phone: +49 7364 208996, Fax +49 7364 209111; e-mail:
h.lettenbauer@zeiss.de, georgi@zeiss.de, d.weiss@zeiss.de

Abstract
X-ray computed tomography (CT) reconstructs an unknown object from X-ray projections and has long been used for qualitative investigation of internal structures in industrial applications. Recently there has been increased interest in applying X-ray cone beam CT to the task of high-precision dimensional measurements of machined parts, since it is a relatively fast method of measuring both inner and outer geometries of arbitrary complexity.

The important information for the user in dimensional metrology is if measured elements of a machined part are within the defined tolerances or not.

In order to qualify cone beam CT as an established measurement technology, it must be qualified in the same manner as established measurement technologies such as coordinate measurement machines (CMMs) with tactile or optical sensors. In international standards artefacts are defined that are calibrated by certified institutions. These artefacts are defined by certain geometrical elements. CT measurements are performed on the reconstructed object volume, either directly or using an intermediate surface-extraction step. The results of these measurements have to be compared to the values of the calibrated elements; the level of agreement of the results defines the accuracy of the measurements.

By using established methods to define measurement uncertainty a very high level of acceptance in dimensional metrology can be reached for the user. Only if results are comparable to standards of the established technologies the barriers of entry into metrology will be removed and all benefits of this technology will be available for the user.
Keywords: Dimensional metrology, 3d computed tomography, coordinate measuring machine, measurement uncertainty, calibration

1. Motivation

Over the last few years there have been numerous attempts to employ X-ray computed tomography (CT) to perform dimensional measurements on parts under inspection. The result of a CT scan displays the part as a three-dimensional image composed of so-called voxels [1]. Each voxel has a gray value that represents the local X-ray absorption density. The resolution of this 3d imaging system is given in part by the number of voxels in the 3d image, which in turn is given by the number of pixels in the detector. By using sub-pixel respectively sub-voxel interpolation, the effective resolution can be increased. Using techniques derived from 2d image processing, 3d voxel images can be evaluated to arrive at dimensional measurements for the scanned parts. This approach is especially advantageous because the 3d image reproduces the complete part including both outer and inner measurement features.
For everyday use in an industrial setting, the key specification of the system is the measurement accuracy/uncertainty. Ultimately the user needs to know whether the part under inspection meets his tolerance requirements and whether his measurement device can answer this question or not. In addition, reproducibility and operator independence are important criteria for the shop-floor deployment of a measurement tool.

Conventional tactile-probe or optical metrology employs internationally accepted standards to make certain that these demands are met. The standards aid the user in comparing measurement results from different systems. For CT metrology, such standards are not yet available. Until such standards exist, Carl Zeiss implements comprehensive tests to provide metrology customers with reliable data concerning the CT measurement performance.

2. Measurement uncertainty in 3d metrology

In conventional metrology, there are different ways of answering the question whether a measurement device is suitable for a measurement task and what accuracy can be reached. Norms and standards define several criteria which permit assessing the accuracy of measurement results, as well as maximum permissible deviations. In Germany, the national standard VDI/VDE 2617 [VDI 86 – VDI 01] is widely used, but the international standard ISO 10360 is gaining acceptance.

Norms and standards can be used to compare different CMMs. However, the CMM accuracy for a given measurement task can only be determined when the task is similar to those defined by the norms and standards [2].

The main purpose of a CMM is to measure distances, so the length measurement error and the probing error are probably the most important specifications. Scanning CMMs can also be used to determine the form of a part, so that a form measurement error can be specified. For a given measurement task, DIN EN ISO 10360 defines a maximum permissible error (MPE) for each applicable accuracy [DIN 03].

MPE values are important criteria for the selection of a measurement tool that is to be used for many different measurements on small lots or single parts. The MPE values should be significantly smaller than the given tolerances (rule of thumb: 1:10). If a CMM is to be used for serial measurements of identical or similar parts, it pays off to perform a “capability study” (similar: GR&R) for the specific measurement task.

All of these criteria are long since established in everyday industrial metrology; however, applying them to CT presents some difficulties. While CT-specific standards are currently being worked on (VDI/VDE technical committee 3.33), conflicting interests of the different parties involved will likely delay finalisation for some time. Indubitably CT is eminently suitable for highly complex measurement tasks, so in the meantime suppliers and users are forced to agree on de-facto standards for specification and certification of CT metrology systems.

For the last four years, Carl Zeiss has been collaborating in this field with Robert Bosch GmbH by supplying a CT metrology service. In order to introduce and establish CT metrology at BOSCH, numerous requirements had to be met which are described in the following section.

3. CMM acceptance for Carl Zeiss Metrotomography at BOSCH Gasoline Systems

Robert Bosch GmbH has detailed internal guidelines defining the requirements for a measurement tool. These requirements encompass all criteria relevant for dimensional metrology and have to be fulfilled by tool manufacturers. Since CT is a new technology in the context of metrology and there are no objective standards yet for measurement uncertainty and machine acceptance, Bosch and Carl Zeiss agreed on a set of detailed acceptance criteria in order to evaluate and realize machine acceptance for the Metrotom 1500 tool in combination with the measurement software Calpyso. The criteria agreed on were:

1. Accuracy and repeatability
2. Operator independence
3. System measurement uncertainty
4. Comparison with reference measurement tools (Zeiss and Mycrona)
    a. Curve measurement (line form)
    b. Inner and outer diameters
    c. Circular position tolerance in 2D
5. Comparison measurement of two parts with color-coded display of the result

These criteria were investigated in the following manner:

3.1 Accuracy and repeatability: Evaluating a measurement process with respect to absolute value and deviation of the measurement results compared to the tolerance field of a measurement feature

For this investigation, a calibrated test piece consisting of 27 ruby spheres mounted on carbon fibre shafts was used, and the sphere-centre to sphere-centre distances of several pairs of spheres had to be measured. In this way, a large number of measurement distances and directions were incorporated in a single test part.

Figure 1. Calibrated test piece for accuracy/ repeatability determination consisting of 27 ruby spheres.

The test piece had to be measured 50 times. For all measurements, the deviation of the measured length L [mm] from the calibrated value had to be less than (5+L/50) µm. In addition, the standard deviation of the measured lengths was required not to exceed a given maximum value (Cg and Cgk $\geq$ 1,33).

3.2 Operator independence: Evaluating a measurement process on serial parts with respect to the influence of the individual operator

In this case, a representative measurement feature of a serial part was selected and had to be measured by three different operators (Bosch and Carl Zeiss) in two runs with each run consisting of 10 measurements. Each operator had to arrange the part inside the measurement volume, perform the CT scan and do the evaluation using the Calypso tool.

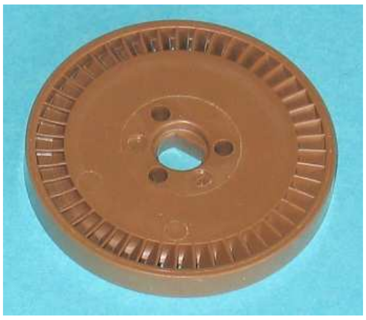

Figure 2. Serial part used for determining operator influence.

As for the previous measurement task, the standard deviation of the different measurements had to be below a given limit (target values: Cg and Cgk $\geq$ 1,33, %GRR $\leq$ 10%).

3.3 Measurement uncertainty

Using the same serial part as in the previous task, the system measurement uncertainty U was determined based on 20 measurements of selected measurement features. Bosch-internal standards give a detailed definition of how to compute U which is not reproduced here. The expanded uncertainty U was targeted to be less than 0.005 mm for the serial part.

3.4 Comparison measurement

The aim of this investigation was to determine to what degree measurement results acquired with the Metrotom 1500 were compatible to results obtained with the measurement tools that were originally used for this task. Such compatibility ensures that existing measurement strategies, embodied in inspection plans, can be used without major modifications. A PRISMO CMM (Carl Zeiss) and an optical 2d measurement tool (MYCRONA) were used as references. Three representative measurement features were selected for a test piece:

a) Curve measurement (line form); target: ΔPrismo-Metrotom ≤ 0,01mm
b) Inner/outer diameters (Tschebyscheff hull and perch diameters, Gaussian mean diameter); target: ΔPrismo-Metrotom ≤ 0,01mm
c) Circular position tolerance with x/y coordinates: comparison of acquired 2D position data with results obtained from polished cut images of the test piece; target: ΔMYCRONA-Metrotom ≤ 0,010mm

Figure 3. Test pieces for tasks a), b) and c).

3.5 5. Comparison measurement of two parts with color-coded display of the result

This task was intended to evaluate the suitability of the measurement tool for “requalification”, i.e., for performing a trend control in ongoing production. The CT scans of two different parts from different production lots had to be compared to each other with regard to the complete geometry, with deviations shown using a color-coded display.

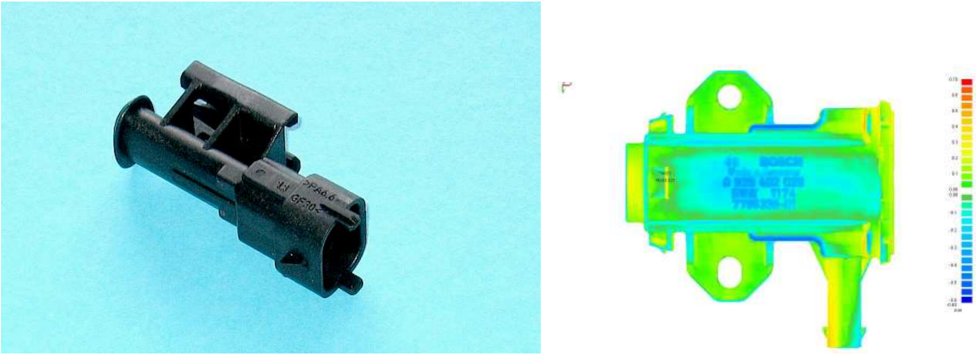

Figure 4. Test piece and evaluation for requalification.

The tasks described above were jointly performed by Bosch and Carl Zeiss between December 2006 and February 2007 using the Metrotom 1500 system. The substantial body of work (nearly 10 man weeks) paid off for both sides: in addition to obtaining a very detailed evaluation of the system performance and accuracy, the user acceptance of the new measuring tool was tremendously increased throughout Robert Bosch GmbH, where it is now operated at full capacity.

4. Conclusions

The unique CT property of being able to acquire the complete volume of a part in a single scan is especially advantageous for parts with complex geometries, where conventional measurement tools cannot access some measurement features and shadowing prevents optical acquisition of the features. In order to qualify CT for dimensional metrology it is important to objectively assess the quality of the results and not be misled by impressive pictures. To perform measurement tasks in an industrial setting, it is paramount to consider the measurement uncertainty. Ultimately the user needs to know whether the measurement features are within the given tolerances and whether the measurement tool is capable of answering this question. Without a doubt there is a need for defining generally applicable and accepted standards for this purpose, and the VDI/VDE technical committee 3.33 „Computed tomography in industrial metrology“ is working on these very issues. Once objective standards are available, CT technology will enjoy a further increase in acceptance by industrial metrology users.

References

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