Improving the dimensional accuracy of computed tomography data obtained with high-resolution 3D X-ray microscopes

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Abstract
Today, 3D X-ray microscopes (XRMs) have the unique ability to achieve higher resolution, non-destructive imaging, within larger parts than traditional X-ray micro computed tomography (CT) systems. Such unique capability is, more and more, of interest to industrial quality control entities as they grapple with small features in precision manufactured parts for various industries such as automotive, electronics, aerospace, medical devices, and additive manufacturing, to name a few examples. Many of today's technology and manufacturing companies require highly accurate metrology, even at sub-micrometer resolutions. This paper describes the development of a package—a solution consisting of hardware and software—for performing highly accurate dimensional measurement with the resolution of 3D XRMs. This new package, named *Metrology Extension* and abbreviated as MTX, specifically conceived for ZEISS Xradia Versa instruments, includes a workflow designed to adjust XRM systems for performing dimensional metrology inspection tasks. Once the MTX workflow is executed, dimensional measurements can be performed in small volumes, in the order of $(5\ \text{mm})^3$ or less, with high dimensional accuracy. After testing the MTX workflow in several Xradia Versa instruments, the metrological performance of such systems was evaluated. The main results show that such systems can produce repeatable and reproducible measurements, with repeatability standard deviations in the order of 0.1 µm, reproducibility standard deviations of about 0.35 µm, and measurement accuracies comparable to those offered by tactile coordinate measurement machines (with deviations within the range of ±0.95 µm). Overall, the MTX is an advancement that enables a 3D XRM instrument to do highly accurate dimensional measurements, thus extending further the imaging capabilities of XRMs into the field of precision dimensional metrology.

Keywords: X-ray computed tomography, 3D X-ray microscopy, dimensional accuracy, high-resolution, metrology

1 Introduction

Three-dimensional (3D) imaging techniques, such as X-ray CT, presently contribute to geometric dimensioning and tolerancing for device components, e.g., mechanical parts, for several technology and manufacturing companies [1, 2, 3]. X-ray CT is used as a tool for nondestructive dimensional quality control in various industries, such as automotive, aerospace, medical devices, electronics assembly and packaging, injection molding plastics, metal casting, and additive manufacturing. However, even under optimal measurement conditions, CT dimensional metrology technologies have traditionally been limited to spatial resolutions no better than 4–10 µm [1, 4]. This leads to several challenges for measuring samples of small dimensions (with volumes in the order of a few mm^3)—e.g., low signal-to-noise ratio in the CT data, and limited detection of contrast changes and spatial details. In addition, in today's precision manufacturing standards, there is a growing demand for tighter tolerances (±25 µm or better) requiring quality control instruments that possess a higher degree of measurement accuracy that what is currently offered by most X-ray CT measuring systems. To overcome some of the limitations of such CT measuring systems, this paper introduces a measurement workflow—a solution consisting of hardware and software—for performing highly accurate dimensional metrology using the resolution capabilities of 3D XRMs.

2 Measurement performance

A metrology workflow developed by Carl Zeiss X-ray Microscopy, Inc., hereafter referred to as *Metrology Extension* and abbreviated as MTX, is used for improving the accuracy of 3D XRM dimensional data. The MTX workflow includes the application of a distortion map correction on the X-ray image projections produced by the detector and a voxel scale correction before XRM data reconstruction. The adjustments for performing dimensional measurement tasks in a ZEISS Xradia Versa instrument can be implemented through the MTX workflow, before scanning workpieces of interest, in a weekly or daily basis. Since strategies for making geometrical distortion corrections in X-ray detectors [5, 6, 7, 8] and image scale corrections [7, 9, 10, 11, 12] are well documented in recent literature, no further expansion on these topics are presented in this article. This paper is focused on the evaluation of XRM measurement performance, via MTX, when dimensioning distances in a multi-sphere standard.

https://doi.org/10.58286/26611

The only two reference documents with procedures for testing dimensional 3D X-ray systems are the VDI/VDE 2630-1.3 [13] and the ASME B89.4.23 [14], which were released as part of the ongoing efforts towards the creation of standard procedures for performance verification and acceptance testing of CT systems used for dimensional metrology. In accordance to the VDI/VDE 2630-1.3 guideline, a (multi-sphere) length standard called the "XRM Check" was developed—at Carl Zeiss Industrielle Messtechnik GmbH [15, 16]—for verifying the accuracy of the CT dimensional measurements on small objects that fit in a 5 mm field-of-view (FOV). See Figure 1.

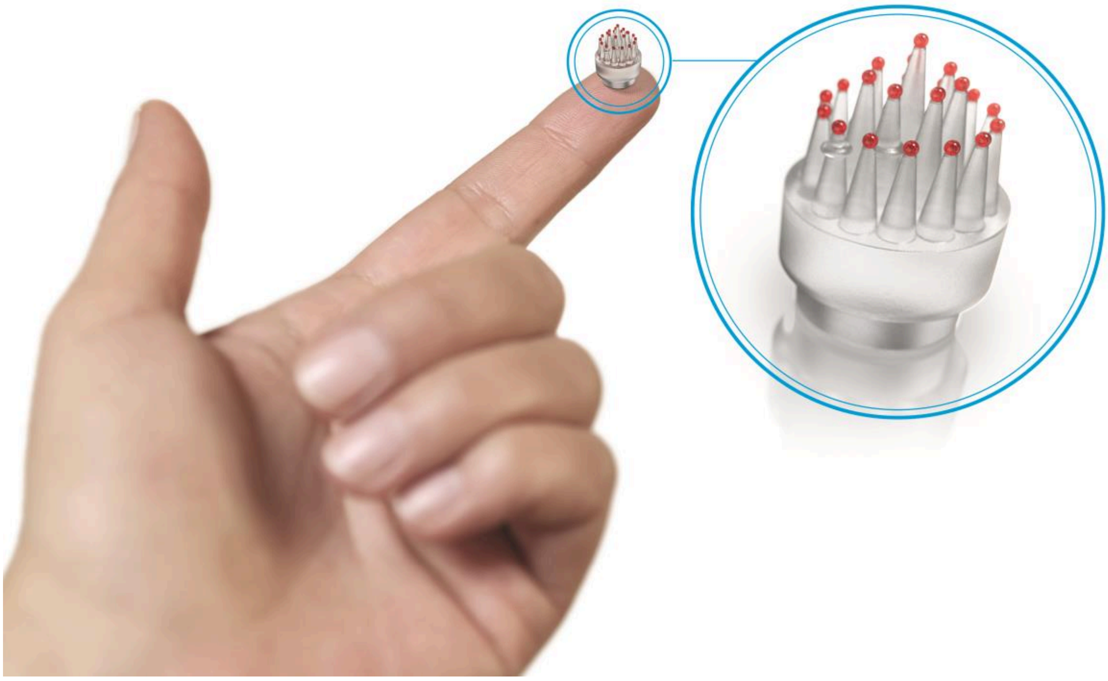

Figure 1: Multi-sphere "XRM Check" composed of 22 ruby spheres (Ø = 300 µm) contained in a cylindrical volume of 4 mm diameter.

This length standard is composed of 22 identical ruby spheres of 300 µm diameter attached to a supporting pillar structure made of fused silica (or quartz glass, with coefficient of thermal expansion $\alpha \approx 0.55$ µm·m^{-1}·°C^{-1}). The spheres roundness (form error) is consistent with the Anti-Friction Bearing Manufacturers Association (AFBMA) criteria for Grade 5 ball or better (tolerances specified by deviations of ±0.13 µm of the combined diameter and roundness of the spheres). Given the simple and well-defined geometrical features of ruby balls, built with low manufacturing inaccuracies and easy to be measured with high accuracy by a tactile CMM, the use of multi-sphere standards is a common and straightforward method for evaluating the performance of CT or XRM systems [17, 18, 19]. The spatial arrangement of the spheres in the XRM Check standard enables a distinctive number of different lengths (at least five different distances), in a total of seven different spatial directions, to implement the acceptance test suggested in the VDI/VDE 2630-1.3 guideline.

The evaluation of metrological performance of the Xradia Versa systems, after execution of the MTX workflow, can be assessed by plotting deviations between CT and CMM[1] data for length measurements, as shown in Figure 2.

2.1 Verifying measurement accuracy

To verify the measurement accuracy (following the VDI/VDE 2630-1.3 guidelines), deviations between CT data and tactile CMM references were computed for various center-to-center sphere distances on the "XRM Check" multi-sphere standard (Figure 1). In this work, the reference measurements for the different sphere distances in the XRM Check standard were calculated from the center positions of the spheres measured by the Federal Institute of Metrology METAS, Switzerland, with an ultra-precise tactile CMM dedicated for calibrating small size objects (METAS µCMM [20]). The reported uncertainty for the reference measurements, expressed as an expanded uncertainty multiplied by a coverage factor k = 2, is

$$U_{ref}(k=2) = 0.138 \ \mu\text{m}. \tag{1}$$

[1] At present, the dimensional measurements obtained by tactile CMMs are generally a more accurate approximation to the 'true values' associated with the measurands in question than the measurements obtained by CT. The measurement uncertainties reported with the CMM technique are typically smaller than the measurement uncertainties associated with CT dimensional data [1, 22, 23], and the traceability chain is also more clearly defined with CMM systems.

After determining the sphere centers with the Gauss (or least-squares) best-fit method, a total of 35 different center-to-center length measurements were evaluated. As seen from Figure 2 (left), the deviations of CT dimensional measurements (from reference CMM data) are confined to a range between ±0.7 µm. This range is well within a conservative specification of MPE (Maximum Permissible Error), for center-to-center sphere distance (SD), of

$$MPE_{SD} = (1.9 + L/100)\ \mu\text{m}, \quad (2)$$

with L measured in mm. The results shown in Figure 2 (left) provide a verification of the accuracy for the metrological capabilities of the Xradia Versa XRMs (in a 5 mm field-of-view) with the added MTX workflow, enabling precision metrology performance over small-scale volumes that are in the order of 125 mm^3 or less.

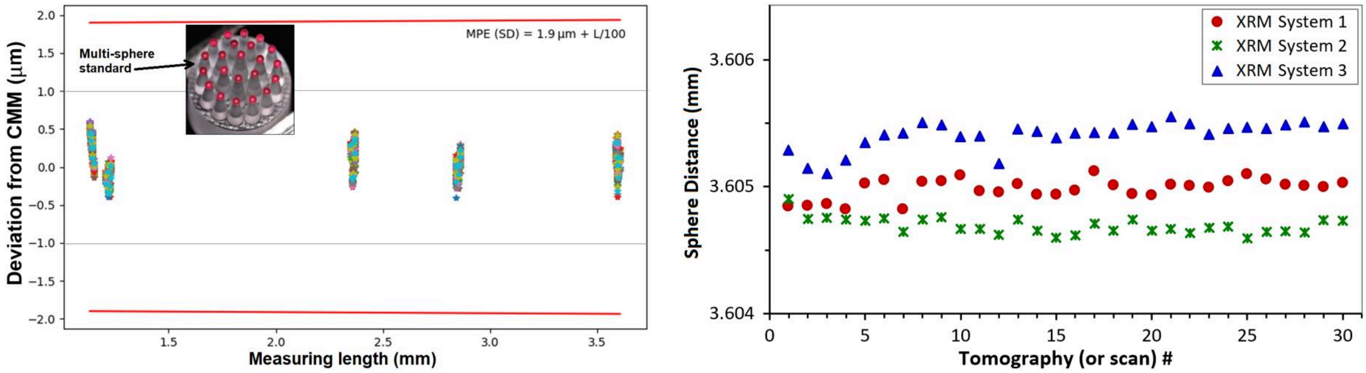

Figure 2: Verifying the measurement accuracy (left) and measurement repeatability (right) of ZEISS Xradia Versa XRMs with MTX.

It is worth noting that, without MTX, the typical deviations of XRM data from calibrated/reference values can be anywhere in the range of 1–30 µm. Figure 3 shows an illustration of MTX-corrected and uncorrected measurements, for sphere center-to-center distances, extracted from 3D XRM data for the XRM Check.

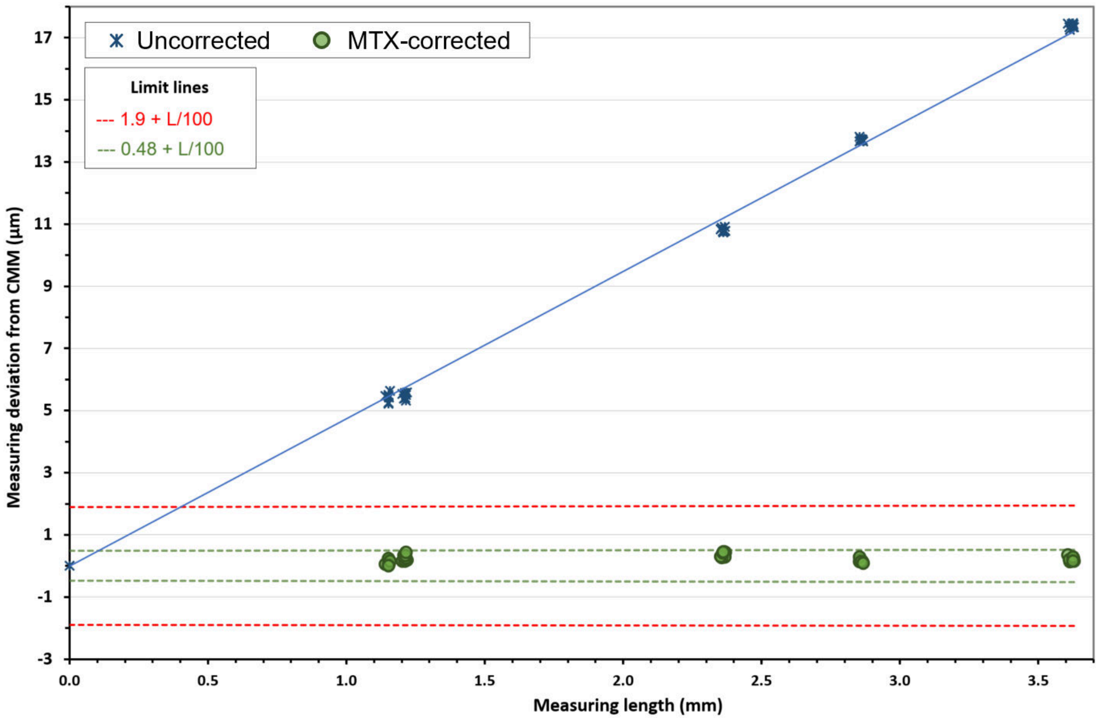

Figure 3: Deviations of XRM dimensional data, from tactile CMM references, after MTX workflow execution on a ZEISS Xradia 620 Versa.

2.2 Verifying measurement repeatability

To verify the measurement repeatability, after the MTX workflow is applied, 30 different scans of a multi-sphere standard were performed with three different systems (i.e., 90 scans total). Figure 2 (right) shows the results of dimensional data for one of the largest center-to-center length measurement (~3.605 mm) in the multi-sphere standard. The repeatability standard deviations of the results assessed per measuring system are $S_1 = 0.08$ µm, $S_2 = 0.06$ µm, and $S_3 = 0.11$ µm; and the reproducibility standard deviation across the three systems is $S_R = 0.36$ µm. From these measures, the deviations between measurements performed on the same feature of length, repeated through 90 different scans, are in the range of ±0.48 µm. The results shown in Figure 2 (right) serve as a verification of the repeatability and reproducibility of the dimensional measurements obtained with the ZEISS Xradia 620 Versa with MTX.

3 Industrial applications

Due to its unique capability for the nondestructive assessment of part geometries not accessible to traditional tactile or optical CMMs, e.g., internal cavities and difficult-to-reach or ‘hidden’ features, the number of industrial applications for X-ray CT in the field of dimensional metrology has been increasing in the last couple of decades [1]. Figure 4 presents examples of dimensional metrology inspection on small industrial devices (a plastic injection-molded connector, the tip of a fuel injector nozzle, and a smartphone camera lens module) performed with ZEISS Xradia Versa systems assisted with the MTX workflow.

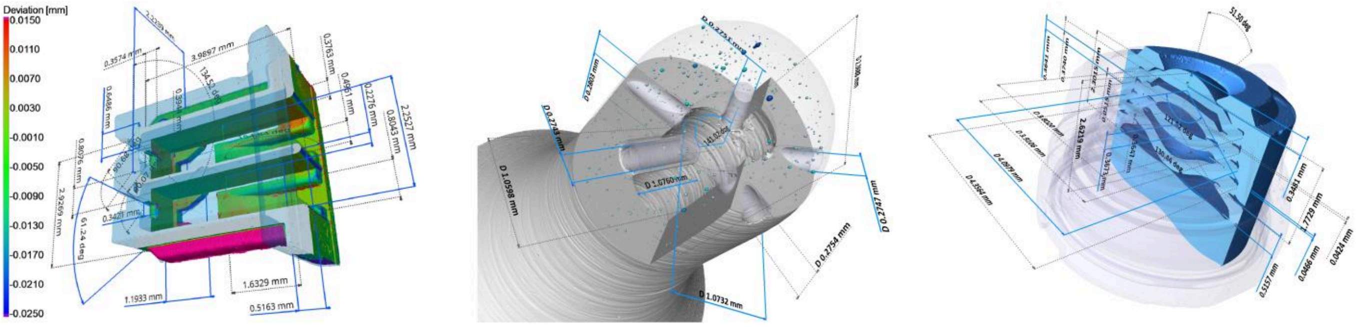

Figure 4: Application examples to illustrate the capability of the MTX workflow for CT metrology inspection of small industrial devices.

4 Conclusions

This paper reports the development of a package, the *Metrology Extension* (MTX), comprised of hardware and software, for performing precision metrology with 3D X-ray microscopes (XRMs). The MTX workflow (for dimensional metrology) has been tested in several ZEISS Xradia Versa XRMs for metrological performance evaluation. The main results show that such systems can produce repeatable and reproducible measurements, with repeatability standard deviations in the order of 0.1 µm, reproducibility standard deviations of about 0.35 µm, and measurement accuracies comparable to those offered by tactile CMM (with deviations within the range of ±0.95 µm). Therefore, once the MTX workflow is executed, XRM systems can be used to measure small volumes, in in the order of $(5\ \text{mm})^3$ or less, with high dimensional accuracy.

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