

RESEARCH ARTICLE

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Extending the measurement capabilities of 3D X-ray microscopy to dimensional metrology

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Received: 16 February 2023 / Accepted: 29 February 2024

Abstract. In the industry of manufactured and assembled devices, the miniaturization and integration of small components with feature sizes on the order of 10 μm or smaller leads to new demands for inspection measurement systems. There are requirements for higher levels of resolution, precision, and accuracy, ideally with technologies that measure internal features and avoid causing damage to the original device. Three-dimensional (3D) techniques such as X-ray computed tomography (CT) may be used to non-destructively inspect internal geometries, or features, that are difficult to reach (or impracticable to access) with tactile probes. Traditional CT systems are, however, limited in resolution and achievable measurement accuracy. One alternative would be to use higher resolution instruments such as 3D X-ray microscopes and expand their measurement capabilities to the field of high precision metrology. This paper demonstrates how to perform non-destructive inspection in small-scale volumes, using a field-of-view (FOV) of about 5 mm diameter, and achieve dimensional measurements that are highly repeatable and accurate (with deviations from calibrated data within the $\pm 1 \mu\text{m}$ range). This capability is relevant for the electronic industry, e.g., for measurements of camera modules or injection molded connectors, and for manufacturing highly efficient components, e.g., fuel spraying injectors and additive manufactured components with small internal features.

Keywords: X-ray microscopy / 3D X-ray microscopes / X-ray CT measurement / computed tomography / dimensional metrology / dimensional accuracy / geometric magnification / optical magnification / CMMs

1 Introduction

3D imaging techniques, such as X-ray CT or X-ray microscopy (XRM), are becoming increasingly important in the field of dimensional metrology and quality control in various industries [1–3]. In today's precision manufacturing standards, there is a growing demand for instruments that possess a high degree of resolution and measurement accuracy. Sub-micrometer resolution XRM systems were introduced more than 15 years ago [4–6], but these instruments have been used mainly for material characterization and non-destructive evaluation (NDE). The main approach for dimensional metrology with 3D X-ray imaging technologies has been the use of CT systems that use flat panel detectors [7,8]. However, even under optimal measurement conditions, CT dimensional metrology technologies have traditionally been limited to spatial resolutions no better than 4 μm to 10 μm . References in the literature reporting high precision dimensional measurements with

XRM instruments are rare [3,9]. Therefore, based on work presented at the 21^{ème} *Congrès International de Métrologie* (CIM 2023), this paper aims to expand the current body of knowledge in that direction with a study that uses a measurement workflow—a solution consisting of hardware and software—for performing accurate dimensional measurements using the resolution of 3D XRM. Evaluation of this newly developed measurement workflow using multi-sphere phantoms shows that it produces repeatable and reproducible data with repeatability standard deviations of about 0.1 μm and reproducibility standard deviations in the order of 0.4 μm .

Section 2 of this article further expands on the developments of 3D X-ray techniques for dimensional metrology. A description of the metrology workflow for 3D XRM is presented in Section 3. Experimental data are also presented to verify the repeatability and reproducibility of the XRM dimensional measurements. Section 4 provides a brief commentary on some industrial applications of the 3D XRM metrology workflow and, lastly, Section 5 summarizes with some concluding remarks. The main results demonstrate that 3D XRM instruments will

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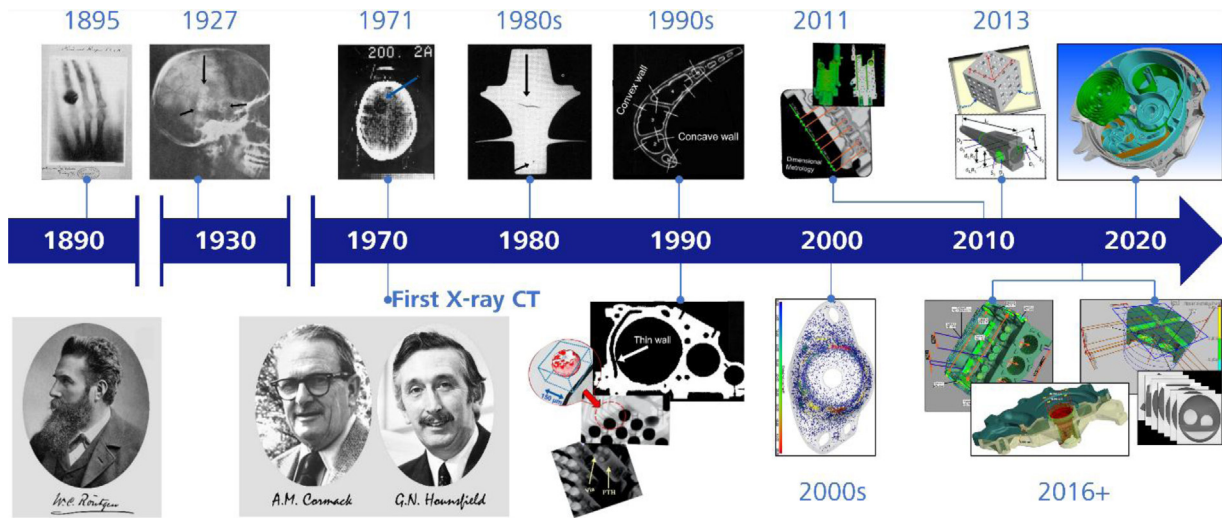


Fig. 1. Developments of X-ray technologies with illustrations of some of its typical uses through history, including applications of non-destructive evaluation and dimensional measurement of industrial component parts. Adapted from reference [13], with pictures of the Nobel Laureates W.C. Röntgen (the discoverer of ‘X-rays’) and A.M. Cormack and G.N. Hounsfield (inventors of X-ray CT).

perform non-destructive measurements in small-scale volumes, using an FOV of about 5 mm diameter, with dimensional accuracies comparable to those offered by tactile coordinate measurement machines (CMMs)—with deviations within the $\pm 1 \mu\text{m}$ range.

2 X-ray techniques for NDE and dimensional metrology

Since the discovery of X-rays (Wilhelm. C. Röntgen, 1895), major advances were produced in the fields of physics and medicine. X-rays became an important tool in medical diagnostics as they allowed doctors to see inside the human body without slicing or cutting it with surgical incisions. Notable technological innovations followed up, with a major breakthrough occurring in 1968 when Sir Godfrey N. Hounsfield filed the patent that led to the construction of the first commercially viable X-ray CT scanner [10]. Although the X-ray CT technique has been predominantly used for medical diagnostics, it was rapidly adopted in the 1980s by the NDE community to see the interior of industrial components (Fig. 1) and identify unwanted defects in them, e.g., voids, cracks, internal thin walls, etc. X-ray CT technologies were already being used to measure geometrical dimensions of manufactured parts toward the 1990s [11,12] and, with further technological improvements, they fully entered the field of dimensional metrology in the mid-2000s, see reference [2]. Today, it is typical to see several manufacturers of CT systems marketing instruments that target industrial dimensional measurements. Some uses of X-ray CT through history are shown in Figure 1, including applications of dimensional metrology.

X-ray CT is not the only technology for NDE quality inspection. There are other technologies such as eddy current techniques, ultrasonic testing, or radiographic projection (i.e., direct 2D X-ray transmission imaging). They may assist in assessing the quality and structural integrity of industrial manufactured components, but there

may be limited measuring resolution (Fig. 2, left). Though not commonly considered as an NDE technique, white light interferometry and direct (non-interferometric) optical imaging may also be used for industrial quality inspection to identify structural and surface defects and are included in the comparison of Figure 2. Interferometry will achieve relatively high imaging resolutions, in the range of nanometers, but is limited to scanning a part’s surface unless there is an aperture opening into the part to inspect it. The best NDE method (currently) that reconstructs complex structures and geometries within a part’s volume, including external and internal surfaces, appears to be X-ray CT, which offers a resolution range of millimeters to nanometers (i.e., sub-micrometer level).

From several types of X-ray CT configurations that may be used to achieve different spatial resolutions, depending on the dimensional size of the sample or FOV to be scanned (Fig. 2, right), most industrial quality inspection solutions, especially for dimensional metrology, have been limited to lensless imaging methods such as micro-CT or macro-CT. Not much progress has been made in industrial dimensional inspection with techniques reaching sub-micrometer spatial resolutions until recently [3,9]. In traditional industrial X-ray CT systems, the main approach has been to use projection-based architectures that employ an X-ray source, a rotating stage to place the measuring object, and a flat panel detector (Fig. 3, left). But, in a flat panel-based CT, the object should be positioned as close to the X-ray source as possible, while remaining within the cone beam¹, to obtain a highly magnified field of view that produces 3D reconstructions with the highest image resolution. In general, in the best-case-scenario for cylindrical objects with diameters in the range of 2 mm to 25 mm, the best spatial resolution

¹ The sample should also rotate on the rotating stage without colliding with the X-ray source.

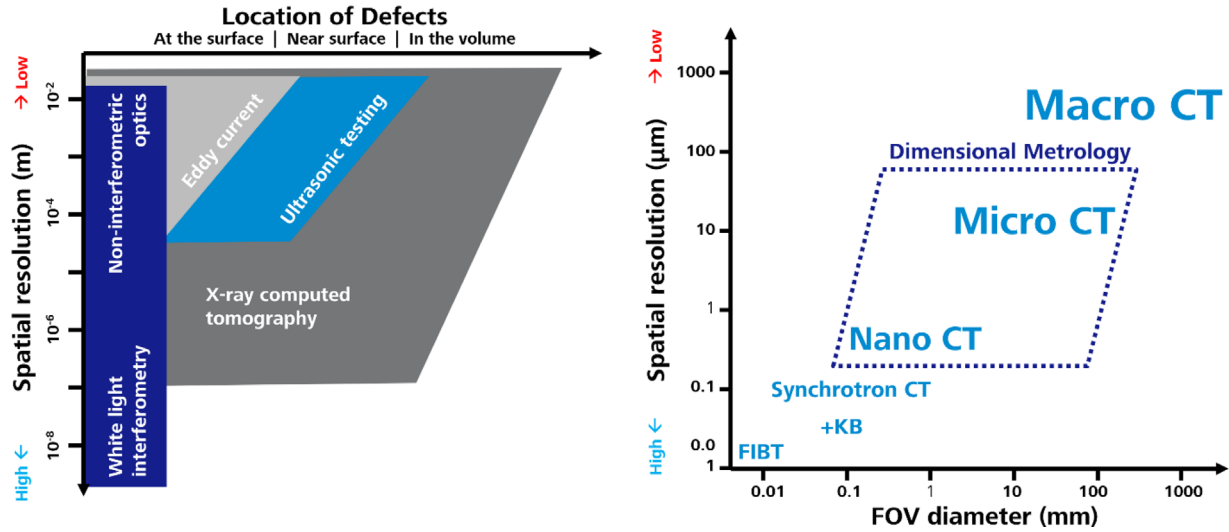


Fig. 2. A comparison of some NDE techniques according to detectable defect location and achievable spatial resolution (left) and typical spatial resolutions achievable by different CT techniques as a function of the FOV diameter (right), highlighting relevant technologies used for dimensional metrology, including synchrotron CT with Kirkpatrick–Baez (KB) mirrors, and focused ion beam tomography (FIBT). Adapted from reference [2], with diagrams that are drawn only for conceptual illustration.

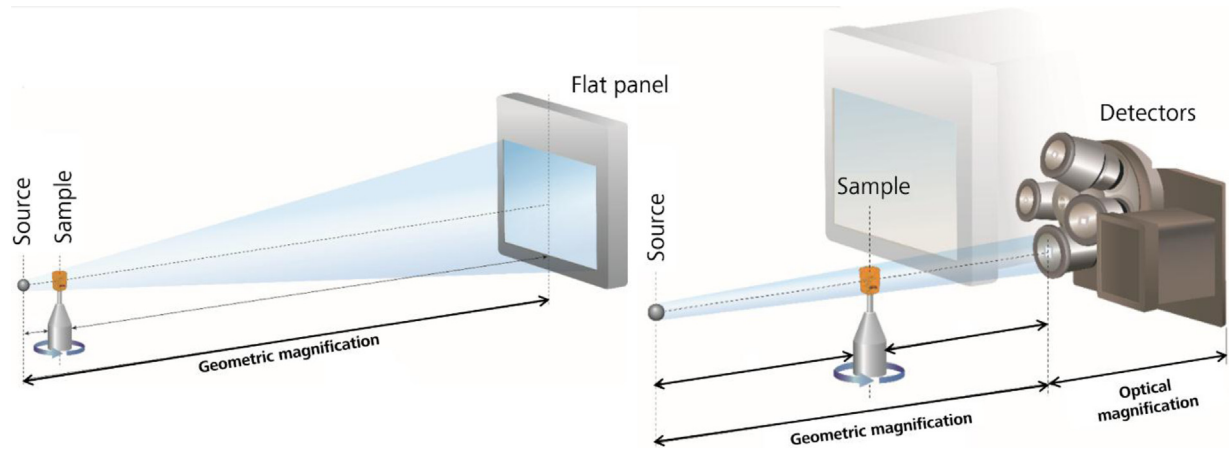


Fig. 3. Schematics of a cone-beam X-ray CT setup with a flat panel detector (left) and the two-stage magnification architecture of a ZEISS Versa 3D X-ray microscope (right) with tunable objectives of different optical magnifications and a $0.4\times$ (faint colored) macro-lens. The Combination of geometric and optical magnification enables higher resolution capabilities in XRM as compared to flat panel X-ray CT systems.

obtained with state-of-the-art commercial CT systems is limited to about a $4\mu\text{m}$ to $10\mu\text{m}$ range [3,8,14]. Larger samples limit geometric magnification, reducing the best achievable resolution of CT scans to several tens of micrometers.

Spatial resolution limitations will hinder essential surface details that might improve the accuracy of CT-based dimensional data. As an alternative to panel-based CT systems, sub-micrometer resolution XRM instruments may be used for dimensional metrology. This article elaborates on that idea by presenting a measurement method that verifies the dimensional accuracy of XRM instruments when targeting dimensional metrology tasks. The main difference of 3D XRM, as compared to traditional CTs, is that they

incorporate a set of optical lenses after X-ray detection to create a scintillator-lens-CCD² detector coupling that optically magnifies the radiographic output (see Fig. 3, right—or alternatively, Refs. [15–17]). The scintillator-lens-CCD coupling is used for the indirect conversion of X-ray photons into electrically charged signals. The X-rays hit a scintillator, which converts the X-ray photons into visible light. The visible light then passes through an optical lens

² A CCD, or charge coupled device, is a metal oxide semiconductor sensor. A CCD is divided into a large array of small light-sensitive cells (known as pixels) to capture light via the photoelectric effect and create a digital image.

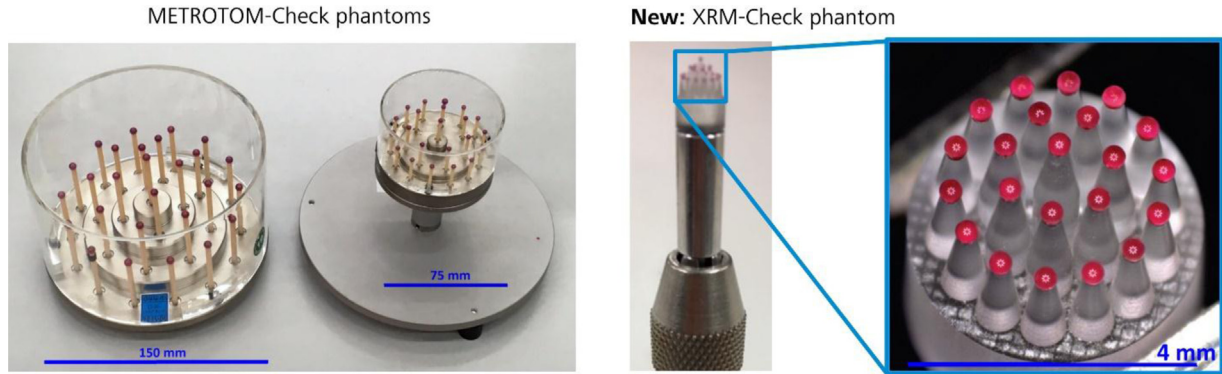


Fig. 4. Two multi-sphere phantoms (left) used to verify the dimensional accuracy of ZEISS Metrotom CT systems and the “XRM-Check” multi-sphere phantom (right) used to extend the measurement capabilities of ZEISS Versa 3D X-ray microscopes.

that projects a magnified image onto the CCD. This strategy reduces effective voxel sizes³ to below 150 nm, producing XRM images with spatial resolutions down to 500 nm [3].

3 An XRM workflow for dimensional metrology

Minimizing scaling errors and improving the accuracy of dimensional measurements requires a suitable method to calibrate the voxel size associated with 3D data reconstruction. In flat panel-based CT systems, voxel-size dimensions are determined by the geometric magnification factor and the X-ray detector’s pixel pitch [14,18]. Methods have already been proposed to determine and correct geometric errors of industrial CT with the use of multi-sphere phantoms [19–22]. Examples of multi-sphere phantoms used in metrology-grade CT scanners are shown in Figure 4. There are other simplistic methods that propose the use of a two-sphere phantom dumbbell, but these are not reliable because they only measure one distance (between the spheres), and therefore rely upon a single data point for interpolation. At best, the two-sphere method would only scale lengths of similar dimensions to that of the distance between the spheres. In addition, current guidelines for performance evaluation of dimensional 3D CT systems, i.e., the VDI/VDE 2630-1.3 [23] and the ASME B89.4.23 [24], require a minimum of 35 or 28 center-to-center lengths to be measured per scan, not just one, in a total of six or seven different spatial directions.

Given the well-defined geometric characteristics of ruby spheres, typically manufactured to very tight tolerances (in the order of $\pm 0.13 \mu\text{m}$ of the spheres’ combined diameter and roundness), the use of ruby multi-spheres is a common method to evaluate the performance of CT systems [25–28]. Using a small multi-sphere phantom, called the “XRM-Check” (Fig. 4, right), a metrology workflow was created at Carl Zeiss X-ray Microscopy, Inc. to extend the measurement capabilities of 3D X-ray microscopes to tasks of

dimensional metrology. Following the VDI/VDE 2630-1.3 guidelines, Carl Zeiss Industrielle Messtechnik GmbH [9,29] developed the XRM-Check length standard multi-sphere phantom. The XRM-Check is composed of 22 ruby spheres ($\varnothing = 300 \mu\text{m}$) mounted on conical pillars and contained in a cylindrical volume 4 mm in diameter and approximately 1.8 mm in height. The supporting pillar’s structure is made of fused silica, or quartz glass, which has a coefficient of thermal expansion $\alpha \approx 0.55 \mu\text{m} \cdot \text{m}^{-1} \text{C}^{-1}$. The spatial arrangement of the ruby spheres in the XRM-Check allows 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 guidelines. A representation of the verification phase of the metrology extension, hereinafter referred to as MTX, is presented in Figure 5. A block diagram of the entire 3D XRM measurement process, with MTX, is shown in Appendix A, Fig. A.1.

While originally designed for ZEISS Versa systems, with further software developments the MTX workflow may be applied to other XRM instruments. Adjustments to the measurement work zone and instrument scan parameters may be implemented via MTX prior to scanning the samples of interest, e.g., weekly or daily. The verification phase of MTX includes comparisons of center-to-center length measurements in the XRM-Check obtained from XRM data with calibrated reference measurements (see Fig. 5). In this work, the reference measurements were computed from CMM data provided by the Federal Institute of Metrology (METAS) in Switzerland. The reported uncertainty for the reference measurements was $U_{ref}(k=2) = 0.14 \mu\text{m}$ [3]. The parameters used for scanning the XRM-Check are listed in Appendix A, Table A.1. Dimensional measurements were performed using Calypso software (Carl Zeiss Industrielle Messtechnik GmbH) [30] with a dimensional metrology probing and sampling strategy that uses a Gaussian multipoint least-squares fit on each ruby sphere to define an average spherical feature, as shown in Figure A.2 of Appendix A (see further details in Ref. [3]).

A set of 35 different center-to-center length measurements, covering at least seven different spatial directions, as suggested by the VDI/VDE 2630-1.3 guidelines, and

³ A “voxel size” represents the dimensions of the basic volume element of the tomographic data into which the 3D reconstructed volume is sub-divided after reconstruction; it represents a “3D pixel” in the volumetric dataset. A unit of “voxel size” does not represent a measure of spatial resolution, see references [2,8].

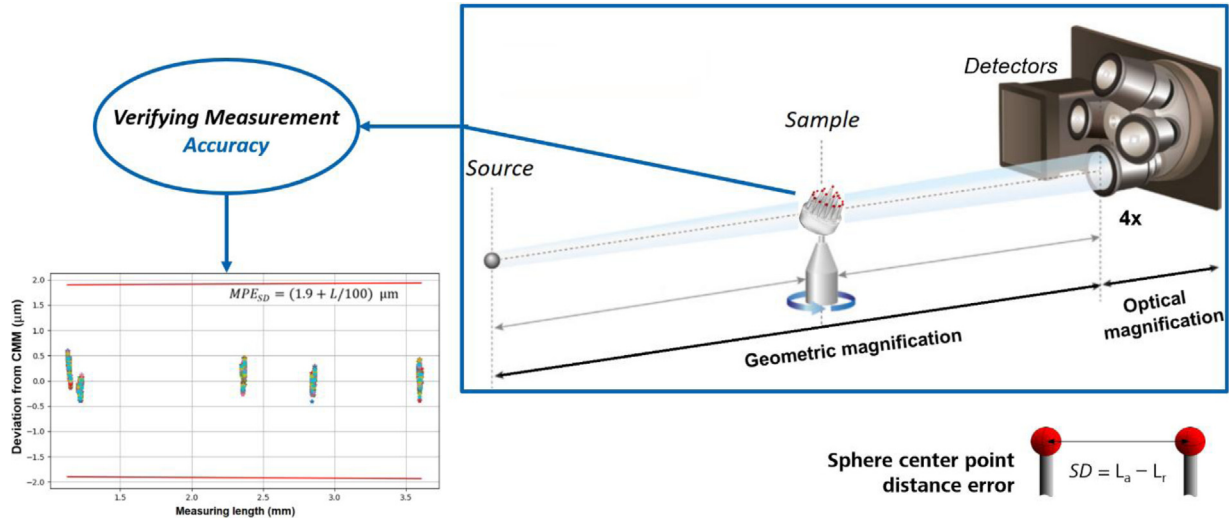


Fig. 5. Verification phase of the MTX workflow, which may be used to check the measurement accuracy of a 3D XRM instrument. The test evaluation computes sphere center point distance errors by comparing CT data with calibrated reference measurements.

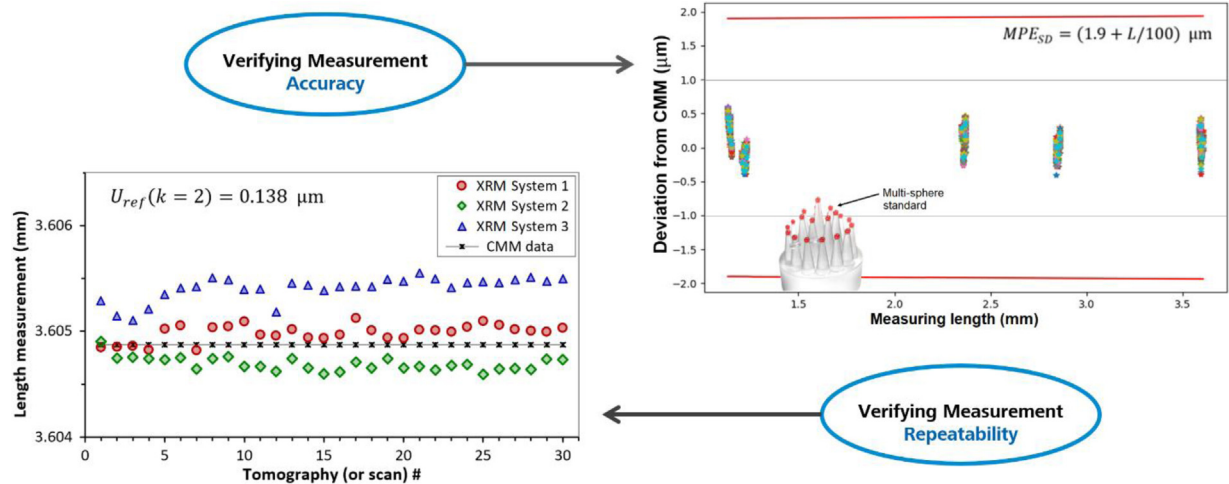


Fig. 6. Test results from verifying the measurement accuracy and repeatability of 3D XRM dimensional data. The charts show deviations of XRM measurements, from CMM-calibrated/reference data, on the XRM-Check (different colored data points represent different test runs). All measurands used for the tests are listed in Table A.2 of Appendix A. The CMM reference measurements, from data provided by the Federal Institute of Metrology (METAS), has an expanded uncertainty of $0.14 \mu\text{m}$ [3].

organized into five groups based on their nominal values, is displayed in Figure 6 (top right). All measurands are listed in Appendix A, Table A.2. The accuracy verification chart, in Figure 6, shows that deviations between XRM dimensional measurements and CMM reference data are confined to $\pm 0.7 \mu\text{m}$. This range is well within a conservative specification of MPE, for center-to-center sphere distance (SD), given by $MPE_{SD} = (1.9 + L/100) \mu\text{m}$ —with L the measuring length in mm; thus, confirming the metrological capabilities of ZEISS 620 Versa microscopes (at FOV = 5 mm) when coupled with MTX.

A total of 30 different scans of the XRM-Check, each repeated with three different XRM systems of the same model (ZEISS 620 Versa), were performed to verify the repeatability and reproducibility of XRM measurements with MTX. Results of XRM measurements for the distance

SD 11-4 (naming convention of Table A.2) which has a nominal value of $\sim 3.605 \text{ mm}$, are shown in Figure 6 (bottom left). Deviations between XRM data and the CMM reference value, through 90 different scans, are in the range of $\pm 0.48 \mu\text{m}$. Repeatability standard deviations evaluated by measurement system are $S_1 = 0.08 \mu\text{m}$, $S_2 = 0.06 \mu\text{m}$, and $S_3 = 0.11 \mu\text{m}$; and the reproducibility standard deviation across the three systems is $S_R = 0.36 \mu\text{m}$. Out of a total of 3150 measurements, after measuring 35 features per scan, the repeatability standard deviations were between 0.04 and $0.15 \mu\text{m}$; with a reproducibility standard deviation range of $0.05 \mu\text{m}$ to $0.45 \mu\text{m}$.

Without MTX, the typical deviations between XRM data and reference values fall anywhere in the range of $1 \mu\text{m}$ to $30 \mu\text{m}$ [3].

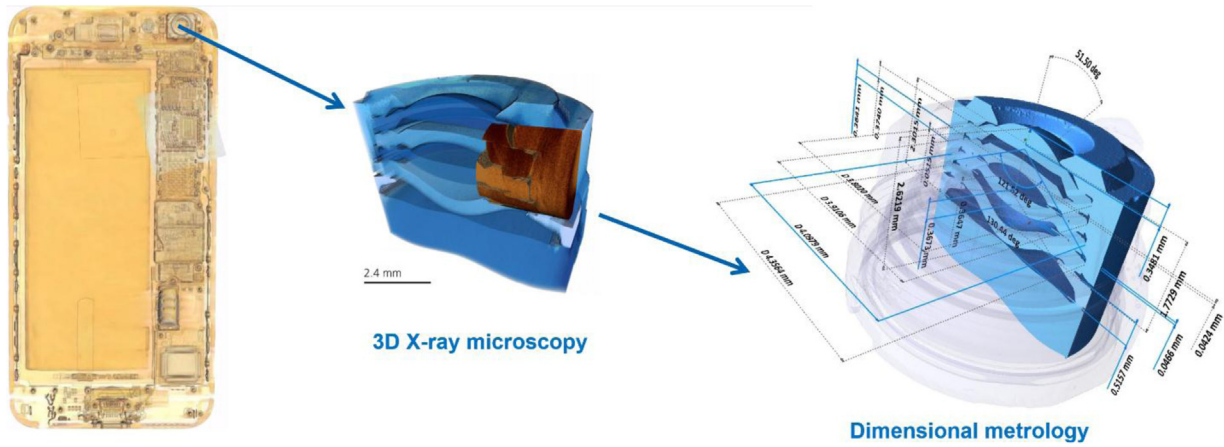


Fig. 7. An example of an application that benefits from extending the measurement capabilities of 3D X-ray microscopes to dimensional metrology would be the evaluation of the geometric properties of a smartphone camera lens assembly.

4 Applications

MTX offers new functionality and opportunities for 3D XRM in the dimensional metrology domain. An example is the non-destructive evaluation of geometric characteristics in the assembled state of a smartphone camera lens module (Fig. 7). Typical geometric properties of interest in a camera lens assembly are the centering interlock diameters, the thickness of the annular wedges, the spaces between the wedges, the lens-to-lens tilt, the vertex heights and centration, etc. The inspection of these features in the assembled state of the camera lens module requires a non-contact, non-destructive measurement method. Since the largest dimension of interest is around 4.4 mm, as seen in Figure 7, an FOV of about 5 mm diameter is enough to capture the main features of interest from the full camera lens module with a 3D XRM scan. Before the acquisition of the XRM dimensional data, the MTX workflow may be applied to verify the measurement accuracy of the XRM system, so that the dimensional measurements extracted from the virtual 3D reconstruction are accurate.

The MTX workflow will undoubtedly support a wider use of 3D XRM for industrial applications, bridging the gap between XRM imaging and dimensional metrology, while preserving high spatial resolution characteristics in the volumetric data reconstruction—a unique feature that is useful for other types of non-destructive evaluation using the same data (e.g., morphological characterization of internal structures, detection of particle inclusions, and pore-size distribution analysis in a material). For various industries, e.g., in the field of additive manufacturing and even in the production of injection molded parts, 3D XRM measurement is even more suitable for geometric dimensioning and tolerancing than tactile or visual inspection techniques. It is a more holistic assessment of a manufactured or assembled device, reconstructing all its internal and external features. By reconstructing all of its internal and external surfaces, 3D XRM plus MTX allows for dimensional measurements that will help

determine deviations in manufactured parts from the original nominal geometry specified by a CAD (computer-aided design) model. This is important for product development, quality assurance of functional characteristics of parts, and assessment of the structural integrity of industrially manufactured components and assembled devices. Additional application examples may be found in reference [3].

5 Conclusion

This paper shows how the limitations of traditional X-ray CT systems when trying to measure small-scale volumes in the order of $(5\text{ mm})^3$ or less, may be overcome by extending standard multi-sphere calibration methods to 3D X-ray microscopes. By using a small multi-sphere phantom and integrating a measurement calibration workflow, called the *Metrology Extension* (MTX), the inspection functionality of 3D X-ray microscopes can be expanded to dimensional metrology tasks.

By performing a series of repeat measurements on multiple instruments, the repeatability and reproducibility of XRM measurements with MTX were verified. Through MTX, deviations between XRM dimensional measurements and reference data may be reduced to $\pm 0.7\text{ }\mu\text{m}$. This small range supports a conservative MPE specification for ZEISS Versa 3D X-ray microscopes, specifically for center-to-center sphere distance measurements (per VDI/VDE 2630-1.3 guidelines), given by $\text{MPE}_{\text{SD}} = (1.9 + L/100)\text{ }\mu\text{m}$ —with L the measuring length in mm. This is a world-leading metrology specification with relevance in non-destructive inspection applications, e.g., for electronics assembly and micro-component manufacturing industries.

More broadly speaking, the above results push the frontier of non-destructive dimensional measurement and open up a wide range of potential applications in quality control of micro-machined parts and multi-component assembled devices, bridging the gap between X-ray microscopy and dimensional metrology.

Lastly, it is worth mentioning that although the MTX was originally designed for the architecture of ZEISS Versa instruments, with additional software development and implementation, the metrology workflow proposed in this article could potentially be applied to other 3D X-ray microscopes.

Acknowledgments

The authors would like to express their appreciation to the reviewers of this paper for the time invested in providing valuable comments and observations during the review process, which have been critically important to the improvement of this manuscript.

Funding

This work was supported by Carl Zeiss X-ray Microscopy. The funders had no role in study design, data collection and analysis, decision to publish, or the preparation of the manuscript. The open access publication fee for this article has been paid by Carl Zeiss Industrielle Messtechnik GmbH.

Conflicts of interest/Competing interests

The authors are employees of ZEISS.

Appendix A

3D XRM measurement process with the MTX workflow

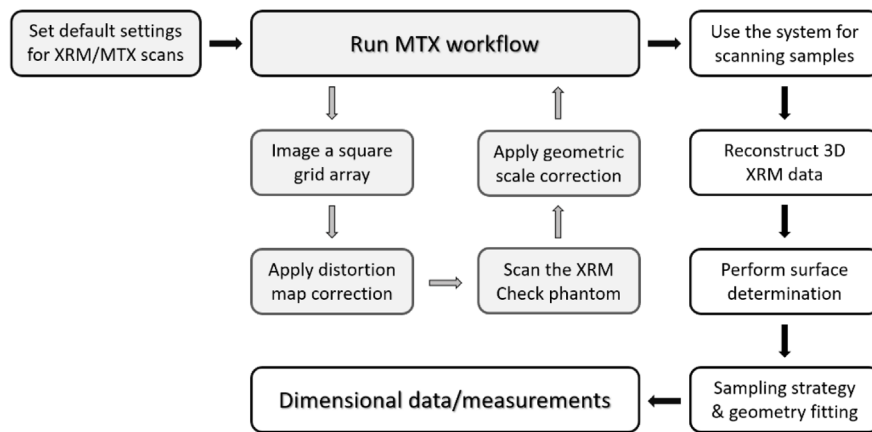


Fig. A.1. MTX workflow integrated into a 3D XRM measurement process so that accurate dimensional data can be provided. Further details describing the measurement process can be found in reference [3].

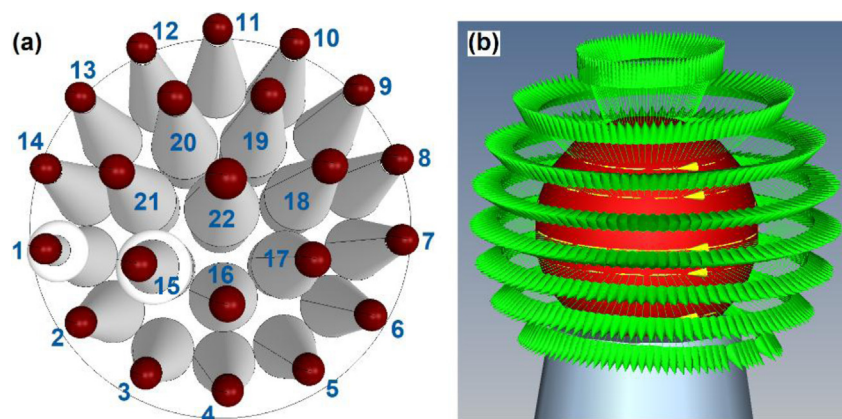


Fig. A.2. Probing/sampling strategy for dimensional measurements in the XRM-Check: (a) sphere identification numbers and (b) multi-point probing strategy to fit spherical features on each ruby sphere [3].

Table A.1. Experimental settings for scanning the XRM Check with a 3D XRM instrument (ZEISS 620 Versa) coupled with the MTX workflow.

3D XRM scanning parameters	
Objective lens	4x
Field of view (FOV)	5 mm
Voxel size (Bin 1)	2.5 μm
Source position	−38 mm
Detector position	15 mm
X-ray tube voltage	90 kV
X-ray tube current	133 μA
X-ray pre-filter	LE2
Exposure time	4 s
Number of projections	800

Table A.2. Measurands associated with center-to-center sphere distance (SD) evaluations in the XRM-Check (sphere identification labels according to Fig. A.2). Grouped into five sets of distances classified by nominal value of length, the measurands are ordered by ascending dimensional magnitude.

Measurand	Short name	Nominal value (mm)
Distance 15-2	SD 2-15	1.134
Distance 16-4	SD 4-16	1.134
Distance 17-6	SD 6-17	1.134
Distance 18-8	SD 8-18	1.134
Distance 19-10	SD 10-19	1.134
Distance 20-12	SD 12-20	1.134
Distance 21-14	SD 14-21	1.134
Distance 15-22	SD 15-22	1.210
Distance 16-22	SD 16-22	1.210
Distance 17-22	SD 17-22	1.210
Distance 18-22	SD 18-22	1.210
Distance 19-22	SD 19-22	1.210
Distance 20-22	SD 20-22	1.210
Distance 21-22	SD 21-22	1.210
Distance 1-22	SD 1-22	2.343
Distance 3-22	SD 3-22	2.343
Distance 5-22	SD 5-22	2.343
Distance 7-22	SD 7-22	2.343
Distance 9-22	SD 9-22	2.343
Distance 11-22	SD 11-22	2.343
Distance 13-22	SD 13-22	2.343
Distance 1-18	SD 1-18	2.850
Distance 3-19	SD 3-19	2.850
Distance 5-20	SD 5-20	2.850
Distance 7-21	SD 7-21	2.850
Distance 9-15	SD 9-15	2.850
Distance 11-16	SD 11-16	2.850

Table A.2. (continued).

Measurand	Short name	Nominal value (mm)
Distance 13-17	SD 13-17	2.850
Distance 1-8	SD 1-8	3.600
Distance 3-10	SD 3-10	3.600
Distance 5-12	SD 5-12	3.600
Distance 7-14	SD 7-14	3.600
Distance 9-2	SD 9-2	3.600
Distance 11-4	SD 11-4	3.600
Distance 13-6	SD 13-6	3.600

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Cite this article as: Herminso Villarraga-Gómez, Naomi Kotwal, Robert Zarnetta, Extending the measurement capabilities of 3D X-ray microscopy to dimensional metrology, *Int. J. Metrol. Qual. Eng.* **15**, 5 (2024)