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CT crown for on-machine scale calibration in computed tomography

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Abstract

A novel artefact for on-machine calibration of the scale in 3D X-ray Computed Tomography (CT) is presented. The artefact comprises an invar disc on which several reference ruby spheres are positioned at different heights using carbon fibre rods. The artefact is positioned and scanned together with the workpiece inside the CT scanner producing a 3D reference system for the measurement. The artefact allows a considerable reduction of time by compressing the workflow of calibration, scanning, measurement, and re-calibration. Furthermore, the method allows a considerable reduction of the amount of data generated from CT scanning. A prototype was calibrated on a tactile CMM and its applicability in CT scanning demonstrated using a calibrated workpiece.

Keywords: Metrology, Calibration, Computed Tomography (CT)

1. Introduction

X-ray Computed Tomography (CT) is a promising measuring technique for the geometrical metrology on a large variety of components [1-2]. Establishment of traceability of CT measurements based on standardized procedures for performance evaluation and correction of the influence factors affecting the entire CT measurement workflow, still represent a challenge. Reference artefacts represent a well-established means to quantify and correct CT errors [1]. Since the introduction of CT, there has been an intense interest in developing new reference structures, mostly inspired by those for conventional CMMs, by adopting a variety of materials and reference elements. In this work, a new type of reference object that can be scanned together with the workpiece, thereby providing traceable information during scanning and post-processing is presented. The manufacture, calibration and preliminary results documenting the applicability of the artefact are described.

2. Design and manufacture of 3D artefact

The CT crown, shown in Figure 1, comprises a rigid base on which a number of spheres are positioned on stems. The spheres are made of ruby providing high contrast and low predisposition to create imaging artefacts. The stems are made from carbon fibre which is a low X-ray absorption material, and have the same diameter but different lengths, giving spatially distributed sphere-to-sphere distances. The base was fabricated via turning, from an invar bar, with a series of though holes to accommodate the stems. The artefact was assembled using adhesive joints. The workpiece is placed inside and scanned together with the CT crown as shown in Figure 1. The artefact can be considered as a reference object with ability to map and correct scale error over the measured scanner volume. Post-processing, including feature evaluations, can be performed similarly to the artefacts meant for scale error correction.

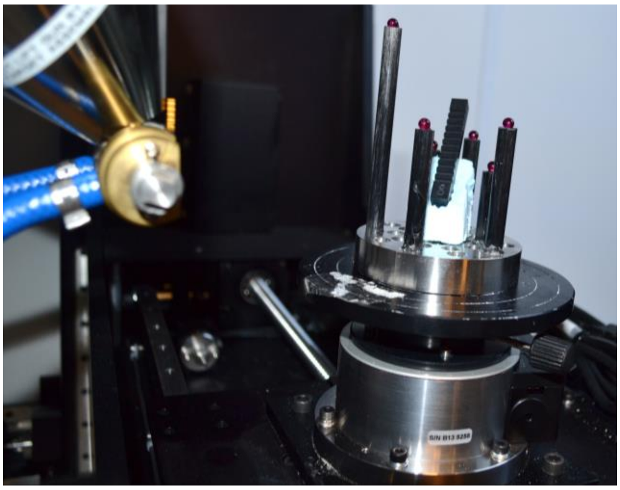

Figure 1. CT crown positioned on a CT scanner rotary table with a miniature step gauge placed inside.

3. Calibration on tactile CMM

Calibration was accomplished using a Zeiss CARAT tactile CMM, characterized by a maximum permissible error MPE = 0.4 + L/900 µm (L in mm). Measurements were performed using a 20 mm long 3 mm spherical probe. A force of 0.05 N was set and its residual systematic contribution corrected numerically. The calibration concerned sphere-to-sphere distances as well as sphere diameters and form errors. Traceability was established using a Zerodur™ hole plate for the sphere-to-sphere distances, and a 8 mm reference sphere for the diameter and form of spheres. 21 points, distributed over three equally spaced sections, are probed on each sphere. Measurements were performed at a temperature of 20 ± 0.5 °C with automatic temperature compensation by the CMM software. 2 calibration cycles of 5 measurements each were performed on the artefact. A calibration uncertainty based on the short term repeatability according to [3] is quantified as follows:

$$U_{cal} = k\sqrt{u_{cert}^2 + u_{tran}^2 + u_{rep}^2} \quad (1)$$

where k is coverage factor (k=2 for a confidence level of 95%), u_{cert} is standard uncertainty from the calibration certificate of the material standard, calculated as $u_{cert}=U_{cert}/k$, u_{tran} is standard uncertainty during the traceability transfer quantified by the standard deviation of n = 5 repeated measurements, and u_{rep} the standard uncertainty from measurement repeatability. Uncertainty contributions such as temperature variations and workpiece expansion coefficient variability were taken into account and found to be negligible. Calibration uncertainties better than 2 µm were obtained for the sphere-to-sphere distances.

5. Application on industrial CT scanner

Initial experiments were carried out to evaluate the applicability of the new artefact using as workpiece a miniature PPS step gauge [4]. The test procedure consisted of two series of scans on a Nikon XT H 225 CT: three repeated scans of the step gauge alone and three repeated scans of the step gauge placed inside the CT crown. For the batch comprising the step gauge alone, a CT ball plate [5] was used as an off-line reference object for the correction of the scale error. The orientation of gauge and the scanning parameters were the same for both configurations.

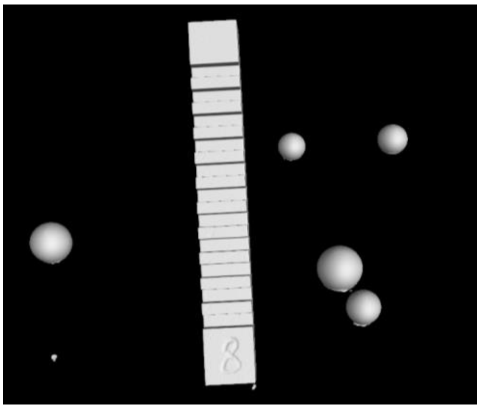

Figure 2. CT scan showing spheres and step gauge.

Image quality analysis, carried out on the uncorrected X-ray projections for both configurations at the same angular position evidenced that the CT crown does not modify the X-ray spectrum, even when spheres and stems fully overlap the workpiece. No scattering due to the invar base was registered analysing the grey value profiles. The determination of the surface, which is necessary before performing evaluations on a data set, was conducted similarly for both configurations on VG studio Max 2.2.6, as shown in figure 2. Measurement accuracy analysis involved 11 measurands including 8 bidirectional lengths (B1 = 2 mm, B2 = 6 mm, B3 = 10 mm, B4 = 14 mm, B5 = 17 mm, B6 = 22 mm, B7 = 2 mm, and B8 = 6 mm), and flatness of 3 flanks (F1 at top, F2 at centre, and F3 at bottom of gauge). The measured values together with their measuring uncertainties, U_{BP} = 3.5 µm and U_{CR} = 3.0 µm for the measurements corrected using CT ball plate and CT crown, respectively, are reported in Figure 3. The measurement uncertainties were quantified for both configurations by taking into account the calibration uncertainty, the CT repeatability, and the temperature variation. Measurements on the gauge carried out in the two different ways were found to be in agreement with En values [6] below 0.45. The results confirmed experimentally the applicability of the artefact.

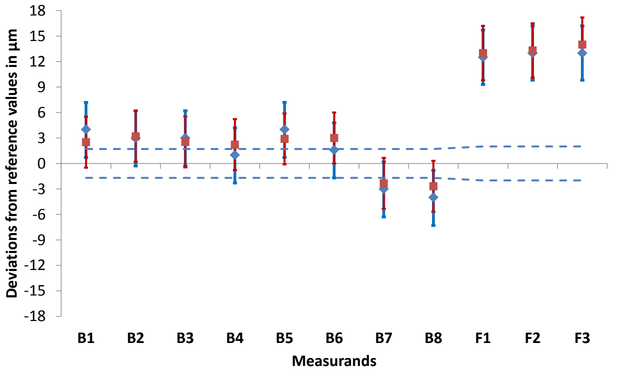

Figure 3. Deviations from CMM with Step gauge alone (blue diamonds) and Step gauge inside CT crown (red squares). Values in µm. Codes: see in the text. Error bars indicate expanded uncertainties of CT measurements at 95% confidence level. Dotted lines show expanded uncertainty of CMM measurements.

6. Conclusions

A novel 3D artefact for concurrent calibration of the scale in X-ray Computed Tomography called CT crown, is presented. A prototype was calibrated on a tactile CMM with an uncertainty below 2 µm, and its applicability demonstrated using a miniature step gauge as workpiece. Scale correction at the same level of uncertainty as when using a CT ball plate for off-line calibration was demonstrated. Compared to existing artefacts, the new on-machine artefact allows a considerable reduction of time (approx. 50%) and amount of data to be stored (approx. 50%) by compressing the full process of calibration, scanning, measurement, and re-calibration, into a single workflow.

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