DOI: 10.7795/810.20180323F

Versatile calibration artefact for optical micro-CMMs based on micro-spheres with engineered surface texture

Rudolf Thalmann[1,*], Alain Küng[1], Anaïs Nicolet[1], Felix Meli[1], Christoph Battaglia[2], Michael Marxer[2], Thomas Jordi[3]

1 Federal Institute of Metrology METAS, 3003 Bern-Wabern, Switzerland
2 NTB Interstaatliche Hochschule für Technik Buchs, Institut PWO, 9471 Buchs, Switzerland
3 Saphirwerk AG, 2555 Brügg, Switzerland

** Corresponding author: rudolf.thalmann@metas.ch*

Keywords : optical micro-CMM, micro-sphere, calibration artefact

Abstract

For the calibration and performance verification of optical micro coordinate measuring machines we have developed an artefact which is based on small spherical elements with optically cooperative surfaces. It is in fact a three-dimensional ball plate with a number of different micro-spheres arranged on an amphitheatre-like glass substrate. The micro-spheres were produced with an adequate quality in terms of roughness and sphericity and an engineered surface texture, which is optically cooperative and thus suitable for optical sensors based on focus variation, chromatic, confocal or astigmatic sensor principles. The application of the calibration artefact allows to evaluate instrument parameters such as volumetric length measurement errors, calibration factors of the three axes separately, orthogonality errors between all three axes, alignment errors of the optical sensor with respect to the instrument axes, as well as scale and form errors of the optical sensor.

1 Introduction

The calibration and performance verification of tactile micro coordinate measuring machines (micro-CMMs) are well established, described in guidelines [1] and a large variety of artefacts was realized and applied in practice [2]. These test artefacts are mostly based on spherical elements, but hardly suitable for optical sensors, where optically cooperative surfaces are required.

The purpose of this study was to develop a versatile calibration artefact for performance verification of optical micro-CMMs, in line with the procedures outlined in the latest draft normative documents. It addresses instruments with a typical measurement volume of a few cm^3, their microscope objectives having a field of view in the order of 1 mm^2. The developed artefact should allow the evaluation of the length measurement error in all three dimensions and possibly further error parameters of the measurement stage of the microscope as well as the errors of the optical sensor within the field of view.

To address the specific needs of optical micro-CMMs it was necessary to produce micro-spheres with an optically cooperative surface, suitable for optical sensors based on focus variation, chromatic, confocal or astigmatic sensor principles. These micro-spheres need to have an adequate quality in terms of roughness and sphericity, but have also to be suitable for tactile reference measurements.

2 Metrological qualification of micro-spheres

Micro-spheres with polished surfaces are commercially available in good quality with diameters down to around 100 µm. By extending their manufacturing process, the company Saphirwerk AG was able to produce ceramic micro-spheres with an engineered surface texture and diameters in the submillimetre range. The challenge was to get cooperative surfaces suitable for most optical sensor principles, but still keeping the form deviation small enough. To obtain optimum process parameters the following relevant characteristics were measured for several production lots of micro-spheres [3]:

- diameter and form deviation (sphericity);
- ISO surface roughness parameters Ra and Rz, and areal surface texture;
- maximum detectable slope angle, dependent on optical sensor principle.

The diameter and sphericity deviations were measured with the METAS micro-CMM [4], using a Ø 125 µm ruby probe and scanning the equator and two perpendicular profiles over the pole of the micro-spheres with a point density of 300 pts/mm (Figure 1, left). The expanded uncertainty for the measured form deviation is estimated to be below 70 nm, as this results from the ISO 10360-4 [5] scanning probe verification test performed on the METAS µCMM, where a similar probing strategy is used.

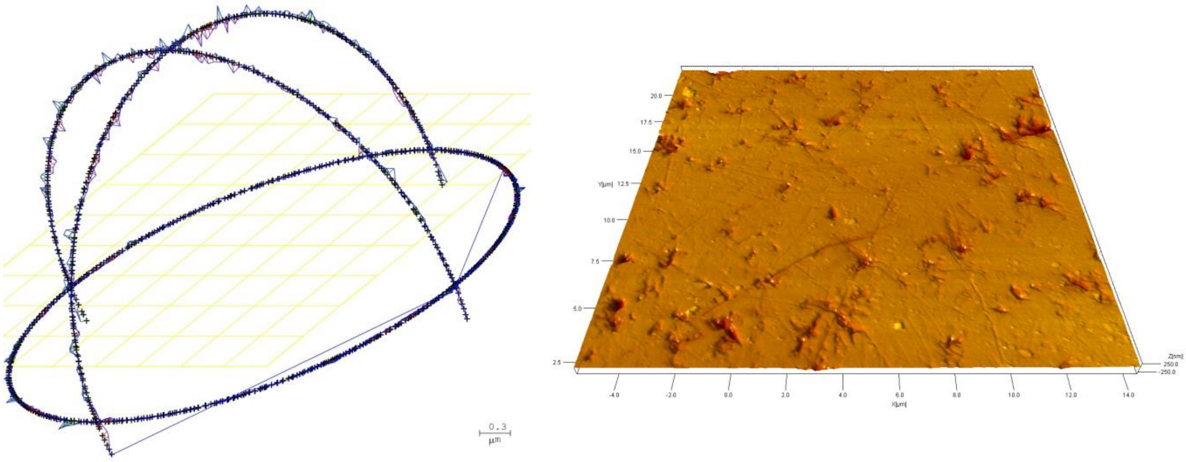

Figure 1: Metrological characterization of a Ø 0.36 mm micro-sphere.
(left) µCMM measured profiles on a micro-sphere for determining the diameter and form deviation.
(right) AFM surface texture measurement on a 20 µm x 20 µm area.

The roughness measurement on the micro-spheres was carried out using a long range AFM profiler [6]. Ra and Rz roughness parameters were evaluated over a cutoff length of 40 µm, after convolution of the profile by a standardized tip radius of 0.1 µm. Figure 1 (right) illustrates an areal surface texture measurement over a central range of 20 µm x 20 µm on the sphere apex.

The maximum slope angle α was determined on a focus variation microscope using a lens with a magnification of 50x or 20x. The criterion for the maximum measurable angle was at the zone where the detectable point density decreased to 50% compared to the point density detected at the sphere apex.

Figure2 shows the evaluation of such a measurement using an Alicona G5 focus variation microscope, on a Ø 0.36 mm ceramic micro-sphere with color-coded deviations to the associated least square sphere with a maximum slope angle of 55°.

Table 1 summarizes the metrological characteristics of the micro-sphere production lots which were finally selected for the calibration artefact described hereafter in section 3.2.

Table 1: Measured values and expanded (k = 2) uncertainties of the relevant characteristics of the micro-sphere lots selected for the calibration artefact.
(conditions: tip radius 0.1 µm, α using magnification 20x for lot 6 and 50x for lots 8 and 9)

Lot #	Ø / µm	Form / µm	*Ra* / nm	*Rz* / nm	α / °
6	359.7 ± 0.3	0.28 ± 0.06	10 ± 1	76 ± 25	55 ± 4
8	782.7 ± 0.5	0.78 ± 0.15	45 ± 4	311 ± 47	60 ± 4
9	2000.4 ± 0.01	0.25 ± 0.05	47 ± 4	325 ± 83	70 ± 4

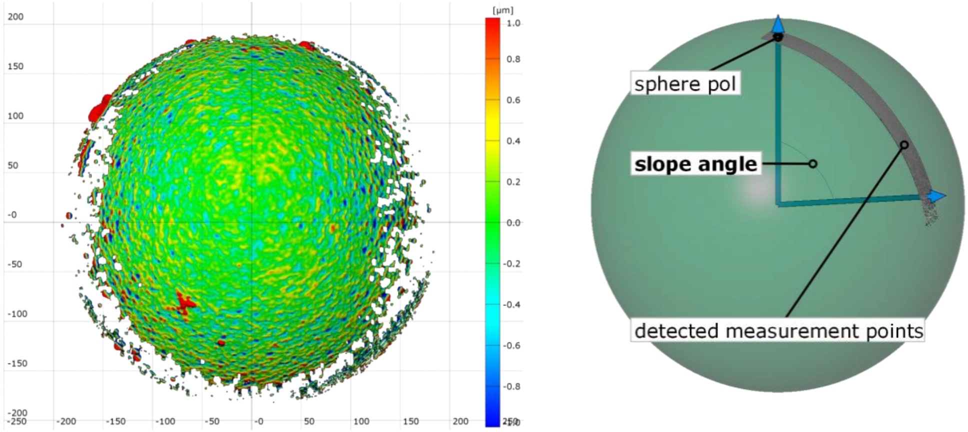

Figure 2: Surface of a Ø 0.36 mm ceramic micro-sphere measured with a focus variation microscope (left) and illustration of the maximum measurable slope angle (right).

3 Calibration artefact

3.1 Design requirements

The calibration artefact shall cover the range of the measurement stage of a typical optical 3D microscope, i.e. a few cm in x- and y-direction and a few mm in z-direction. Similar to a 3D ball plate, as used in conventional coordinate metrology, a number of micro-spheres are to be suitably arranged in all three dimensions within the measurement volume. In order to comply with requirements of ISO 10360-2 for coordinate measuring machines [7], space diagonals with at least 5 equidistant spheres should be realised. In addition, features which allow to determine the probing errors related to the optical sensor shall be available [8]. The artefact should be suitable for imaging probing systems and optical sensors based on focus variation, chromatic, confocal or astigmatic sensor principles.

3.2 Artefact realisation

Figure 3 shows an artist view of the close to final product prototype artefact. On an amphitheatre-like glass substrate 16 ceramic micro-spheres of Ø 0.8 mm are glued, arranged on a 40 mm x 40 mm pattern on 6 different heights, actually forming a 3-D ball plate. In addition, there is an insert with 7 smaller spheres of Ø 0.36 mm, forming two square patterns of 0.45 mm and 1.26 mm side length, allowing for tests within the field of view of microscope objectives of different magnifications. Finally with the help of a 2 mm sphere form and size errors of the optical sensor may also be assessed. Both the glass substrate and the micro-spheres have an optically cooperative surface.

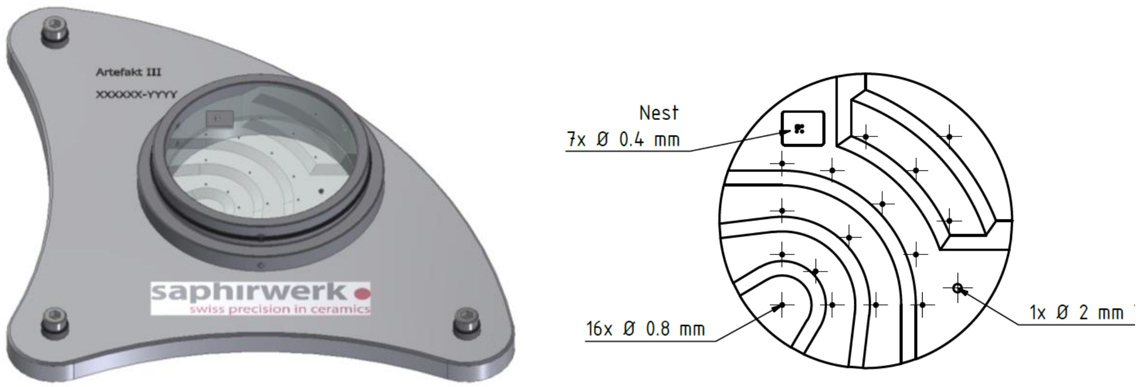

Figure 3: 3-D calibration artefact with 16 spheres (Ø 0.8 mm) arranged on a 40 mm x 40 mm pattern on 6 heights, an insert of 7 spheres (Ø 0.36 mm) and 1 sphere (Ø 2 mm) on a glass substrate.

3.3 Calibration and stability of the artefact

The 3D-coordinates, diameters and form errors of the spheres from the amphitheatre-like artefact are calibrated with the help of a tactile µCMM [4], using a Ø 125 µm ruby probe and scanning each micro-sphere according to the scheme of Figure 1, left with a point density of 300 pts/mm. The expanded uncertainty for the coordinates of the sphere centres, the diameters and form deviations is dependent of the sphere's roughness and estimated to about 0.2 µm.

The stability of the artefact could so far be estimated based on two calibrations carried out in a six months interval between June and December 2017. Figure 4 shows the differences between the two calibrations for all spatial distances between the spheres. They are all within ± 0.15 µm and thus largely within the uncertainty of these differences. It can be concluded, that both, the calibration uncertainty and the stability of the artefact are small enough to make the artefact suitable for the verification instruments with specified spatial errors down to about 0.5 µm, which covers to our knowledge most of commercial optical µCMMs.

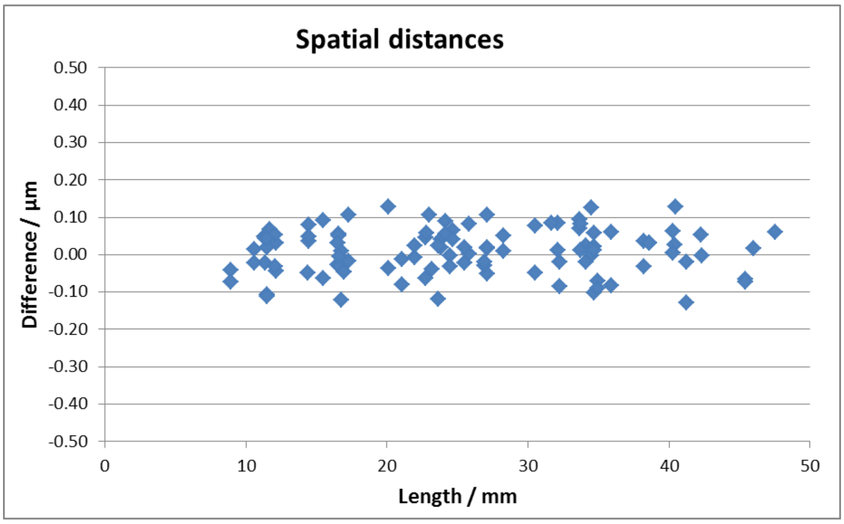

Figure 4: Differences of all measured spatial distances between two calibrations carried out in a six months interval.

4 Application of the artefact for instrument verification

4.1 Analysis of measurement data

The performance verification of a coordinate measuring machine ideally covers the following features: Measurement of the centre coordinates and the diameters of all 16 spheres of Ø 0.8 mm using the stage of the instrument. Further on, measurement of the centre coordinates, the diameters and the form deviations of the 4 inner or the 4 outer spheres (Ø 0.36 mm) of the nest within the field of view of the optical microscope, dependent on the magnification, and possibly measurement of the diameter and form deviation of the Ø 2 mm sphere within the field of view of the optical microscope.

From these data, the following parameters according to ISO 10360-7 [8] can be evaluated:

- Volumetric length measurement errors, based on all 120 mutual distances of the 16 sphere centres. These may be compared to the unidirectional length measurement error E_U as specified by the manufacturer;
- Calibration factors for each of the three axes, based on the x-, y-, and z-coordinates of the 16 sphere centres compared with the calibrated values. These calibration factors may be used to correct for the scale factors of the instrument stage within the measurement volume;

- Squareness errors between all three axes, the x/y-squareness error E_{SQ} e.g. based on the deviation of the y-coordinates of the sphere centres versus their x-coordinate. These values may also be used to correct for the orthogonality error of the instrument stage within the measurement volume;
- Imaging probe unidirectional length measurement error E_{UV}, based on the errors of 6 mutual distances of the 4 small spheres in the nest measured within the field of view of the optical sensor.
- Imaging probe bidirectional length measurement error E_{BV}, based on the average deviation from the calibrated diameter of the 4 small spheres in the nest measured within the field of view of the optical sensor, or based on the deviation from the calibrated diameter of the 2 mm sphere.
- Probing error of the imaging probe P_{FV}, based on the measured form (sphericity) deviation on one of the spheres (Ø 0.36 mm, 0.8 mm or 2 mm) with respect to a least squares fit within the field of view of the optical probe.
- Alignment of the optical sensor with respect to the stage axes: If the nest with the smaller spheres is measured within the field of view of the microscope in the same coordinate system as the 16 larger spheres of the artefact, it is possible to determine the alignment error of the optical sensor system with respect to the axes of the instrument stage. In particular any rotational error of the image sensor with respect to the stage x/y-coordinate system.

Further parameters as defined in ISO 10360-7 [8] might be evaluated as well.

4.2 Dedicated software for measurement data evaluation

METAS has developed a dedicated software for the evaluation of the measurement data. This software is delivered together with each calibration certificate, contains the calibrated values for the artefact and allows to determine all parameters mentioned in section 4.1. Figure 5 shows a screenshot of the front panel of the software.

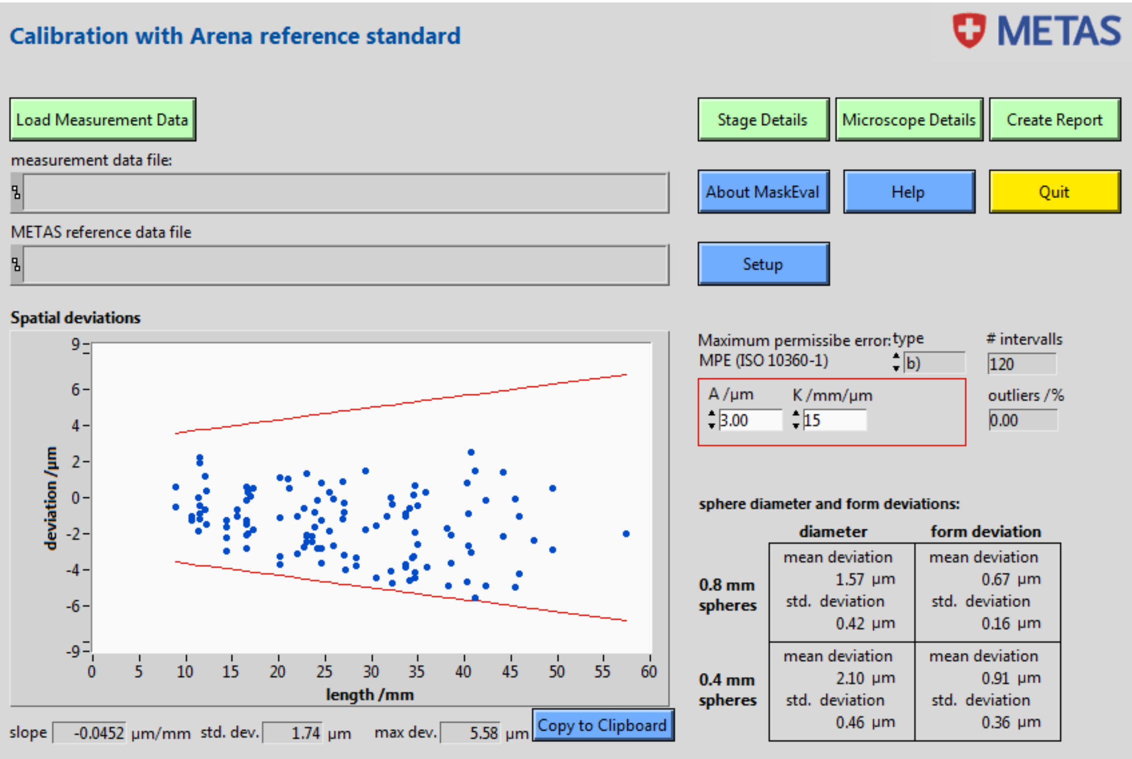

Figure 5: Screenshot of the data evaluation software.

4.3 Performance verification of a focus variation optical micro CMM

The use of the calibration artefact has been validated by several project partners verifying the performance of their instruments. As an example the results obtained using an Alicona InfiniteFocus micro-coordinate measuring instrument based on focus variation are presented. Results are shown on the screenshot of Figure 5: The standard deviation of the errors of all 120 spatial distances is 1.7 µm with a maximum error of 5.6 µm. The bidirectional length measurement error is within the limits $E_{\mathrm{B}} < \left(3 + \frac{L}{15}\right) \mu m$, where L is the length in mm. The negative slope which can be seen in the point cloud of Figure 5 is mainly due to a scale factor error of the x-axis evaluated to -0.038 µm/mm. Furthermore it has been shown that the axes of the image sensor are rotated by an angle of 0.05° with respect to the stage axes. The adjustment of these two errors could probably improve the overall performance of the instrument to some extent. Finally, the evaluation of the measured diameter and sphericity of all spheres showed, that the sphere diameter is measured roughly 2 µm larger than the calibrated value and that the form deviation is overestimated by about 0.7 µm.

5 Conclusion

We have developed a versatile calibration artefact for the performance verification of optical micro coordinate measuring machines. It is based on a 3D ball plate with optically cooperative micro-spheres arranged on a transparent glass substrate in an amphitheatre-like design. It allows to evaluate most of the relevant instrument error parameters in one setting. In test measurements the artefact turned out to be stable and its application for performance verification proved to provide valuable results on various instruments. The industrial project partner plans to commercialize the described calibration artefact.

Acknowledgement

The support from the Commission for Technology and Innovation CTI of the Swiss Confederation for the project 16744.1 PFNM-NM is highly appreciated.

References

[1] VDI/VDE 2617, Part 12.1, 2011 Accuracy of coordinate measuring machines - Characteristics and their testing: Acceptance and verification tests for tactile CMM measuring microgeometries.

[2] Claverley JD, Leach RK. 2014 A review of the existing performance verification infrastructure for micro-CMMs. *Precis. Eng.* **39** 1 - 15

[3] Küng A, Nicolet A, Meli F, Thalmann R, Battaglia C, Marxer M, Jordi T. 2016 Metrology on micro-spheres with engineered surface texture, *Proceedings of the 16th euspen conference*, Nottingham, UK

[4] Meli F, Küng A, Thalmann R 2007 Ultraprecision micro-CMM using a low force 3D touch probe, *Meas. Sci. Technol*. **18**, 319-327.

[5] ISO 10360-4:2000, Geometrical product specifications (GPS) - Acceptance and reverification tests for coordinate measuring machines (CMM) - Part 4: CMMs used in scanning measurement mode.

[6] Meli F and Thalmann R 1998 Long range AFM-profiler used for accurate pitch measurements, *Meas. Sci. Technol.* **9**, 1087-1092.

[7] ISO 10360-2:2009, Geometrical product specifications (GPS) - Acceptance and reverification tests for coordinate measuring machines (CMM) - Part 2: CMMs used for linear dimensions.

[8] ISO 10360-7:2011, Geometrical product specifications (GPS) - Acceptance and reverification tests for coordinate measuring machines (CMM) - Part 7: CMMs equipped with imaging probing systems.