Metrological Approach for Testing Performance of Optical 3D Measurements Systems

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Abstract. For quality control purposes, many manufacturing industries perform dimensional metrology checking processes that often necessitate the use of precision optical 3D measurement instruments, such as fringe projection systems, laser scanners and other similar non–contact systems. The typical measurement accuracies of commercially available instruments are down to few micrometers. In order to assure traceability of measurements to the SI, the meter, these instruments are normally calibrated by using different precision measurement standards, such ball bars and special 3D set-ups. With these optical standards, a range of different kinds of optical measurement instruments, together with their associated internal reference scales and image processing algorithms can be evaluated and then verified.

Recent research work in the field 3D optical artefact calibration is presented in this book. In addition, a tetrahedron ball standard and a method for calibrating 3D optical measurement systems are presented. The outcome of the presented research is a calibration procedure with approved measurement uncertainty that has already been accredited by the national accreditation body.

Keywords: Calibration · Traceability · Optical CMMs

1 Introduction

With the initial development of coordinate measuring machines (CMMs) in the 1970s, 3D metrology has become established in industry. Since that time, industry together with scientific metrology institutes have developed test procedures which enable machine manufacturers as well as end users to evaluate the performance of different types of CMMs [1, 2].

The specified acceptance and re-verification procedures have meanwhile been established in many national and international guidelines [3]. However, traceable measurements on CMMs are only possible by using a well–known substitution method based on calibrated artefacts and by employing advanced virtual CMM techniques [4, 5].

Apart from tactile measurements, traceability of optical 3D measurements [6, 7] is still an open issue, as a qualified statement of the task specific measurement uncertainty, requested by international standards like ISO 9001 [8] can hardly be given. Traceable standard reference artefacts and procedures for both calibration and

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verification of optical 3D systems practically do not exist. Some forms of equipment verification tests are performed by producers of measuring systems, but these employ non–validated procedures in-conjunction with in–house standards. Unfortunately no accredited or national laboratories are involved in the traceability chain. Thus demonstration of the conformance of a piece of measuring equipment to meet specifications according to ISO 14253-1 [9] is consequently not possible. This leads to increasing costs as it is not possible to distinguish reliably between acceptable and non–acceptable parts, especially where tolerances are small compared to the measurement uncertainty.

For the above reasons, the consortium of the European project iMERA Plus JRP T3.J2.2 NIMTech project [10] decided to develop different types of 3D artefacts and corresponding procedures for verifying the freeform measurement capability of optical and tactile co–ordinate measuring systems. A range of reference artefacts has been developed, allowing the performance of optical–based 3D measurement systems, such as fringe projection, laser scanners and other similar non–contact systems to be verified against a set of known surface conditions. The purpose of these artefacts was to demonstrate the dimensional measurement capability of selected optical–based 3D measurement technologies to measure specific forms and various surface conditions, rather than to be universal standards [11].

All the standards were designed in accordance with industrial lead requirements. They are now available from the respective national metrology institutes (NMIs) and can be supplied with appropriate calibration data. High precision specifications and associated metrological characteristics were confirmed by measuring all the artefacts on different tactile and optical CMMs using the facilities from all the three participating NMIs.

These developments were performed by three project partners, namely National Physical Laboratory from United Kingdom (NPL), Physikalisch–Technische Bundesanstalt from Germany (PTB), and Laboratory for Production Measurement from the University in Maribor, which is representing the Metrology Institute of the Republic of Slovenia (MIRS/UM-FS/LTM).

This article is presenting the tetrahedron standard developed by MIRS/UM-FS/LTM and its application in assuring traceability of optical 3D fringe projection measurement systems.

2 Standards and Procedures

2.1 Documented Standards

From around 1994 onwards, ISO 10360-2 series part 3, “Geometrical Product Specifications (GPS) acceptance and re-verification tests for coordinate measuring machines (CMM)” [3] has been available to assist in verifying the performance of such machines. Until 2011 there were 6 parts of this document, each part specialising in different technical areas. For example, Part 1 describes fundamental CMM “Vocabulary” and Part 6 describes “Estimation of errors in computing Gaussian associated features”. This standard does not cater for optical based coordinate measuring systems, such as those employing laser triangulation or fringe projection scanners [7]. In 2011, ISO 10360-2 Part 7 “CMMs equipped with imaging probing systems” was introduced.

In 2002, a German guideline VDI/VDE 2634 [12] was introduced. This guide relates to optical–based 3D scanning systems and currently consists of three parts:

- Part 1: “Imaging systems with point-by-point probing”;
- Part 2: “Optical systems based on area scanning”;
- Part 3: “Multiple view systems based on area scanning”;

This VDI/VDE guideline defines a particular way of measuring a reference artefact, which is typically used to define a spatial length or simple forms (sphere, plane) to a high accuracy. Although much more suited to optical systems than the ISO 10360-2, parts 2 and 3 of the VDI/VDE 2634 guideline are more relevant to surface scanning. However the guidelines do not cover performance verification of freeform surface measuring systems.

2.2 Standards of Measurement

A variety of standards or artefacts can be used for calibrating and testing performance of CMMs [13, 14]. Commercially available standards, like gauge blocks, balls, internal and external cylinders, step gauges, etc. can be used on their own or in different combinations. In addition, different kinds of special 2D and 3D artefacts have been developed. Most of them consist of basic standards in different spatial or planar configurations. In most cases, such artefacts are equipped with external and internal balls.

A ball is the most common element currently used for determining metrological characteristics of optical 3D measurement systems such as fringe projection, laser scanners, photogrammetric and other similar non-contact systems. Artefacts [13] are produced in the form of a plane and a single ball or a ball-bar with two or more balls attached as illustrated in Fig. 1.

Fig. 1. Existing artefacts for testing optical CMMs [11, 13]

Verification of these non-contact measurement systems is complex and useful guides such as the VDI/VDE 2634 2 series [12] describe methods to demonstrate capability using test artefacts (see Fig. 2) with prismatic features, such as spheres, ball-bars and planes. However, the guides do not extend to fully address performance verification when freeform surfaces are to be measured using optical-based techniques. In order to verify most parts of the measurement volume, the verification artefact needs to be measured in several positions within the measuring volume. VDI/VDE 2634 states at least three arbitrary positions need to be chosen for the measurements, but it is recommended to use five to seven positions. Especially for multiple view scanning systems, the total number of scans resulting from at least five different sensor positions for at least three artefact positions is a minimum. Thus the number of measurements required can dramatically increase in number, from typically 15, to as many as 40 data sets. Thus this type of verification approach can be extremely time consuming and result in high costs.

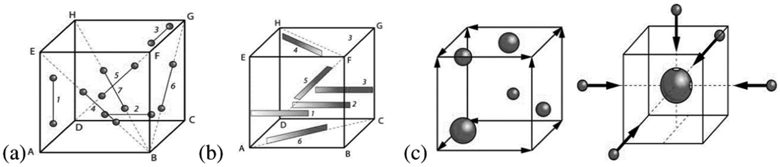

Fig. 2. Verification tests according to VDI/VDE 2634: (a) determination of sphere spacing error, (b) determination of flatness error, (c) determination of probing error

2.3 Existing Procedures

Most commonly three types of procedures are used for assuring traceability of 3D measurements:

- performance verification tests [2, 15];
- task related calibration; and
- Virtual CMM [4, 5, 12];

Performance tests serve as a tool for confirming measurement uncertainty declared by a CMM manufacturer. A variety of 1D, 2D and 3D standard artefacts are employed for performing such tests. The application of such tests is designed to be straight forward and is aimed to be carried out relatively quickly and in a financially economical way. Therefore, they are widely applied in industry for assuring traceability of industrial measurements [16, 17].

Task related calibrations, which employ the comparator principle, are often used for specific measurement tasks, where simple quantities need to be measured or calibrated to a high accuracy. The measurand is compared with a calibrated standard of similar form and dimension. This procedure cannot be used for complex forms and is quite time consuming to perform. For this reasons it is not normally employed for assuring traceability of precision industrial measurements.

The Virtual CMM [5, 18] represents the highest level of assuring traceability of coordinate measurements. It is the only method for performing calibrations using CMMs, in strict accordance with the definition of the term ‘calibration’. Significant random and systematic errors of a CMM are modelled to characterize the kinematic behavior of the CMM and its probing process. Therefore, all input parameters have to be determined traceable to SI units. For instance these are geometrical errors of the CMM’s guides or probing errors. The methods for determining the input parameters are relatively time consuming and as a consequence also quite expensive. However, often the Virtual CMM is used by calibration laboratories, which calibrate complex 2D or 3D standards.

3 Tetrahedron Artefact for Testing Performance of Optical CMMs

Experiences of MIRS/UM-FS/LTM in traceability of optical measurements were limited to 1D [19] and 2D artefacts before joining the project [10]. Tetrahedronal verification artefacts that were developed during the project were the first 3D artefacts designed by this laboratory. The purpose of these artefacts is for testing the performance of fringe projection and similar 3D optical measurement devices with both single scan and multiple scan measuring capabilities [11].

In order to minimize verification time and still comply with standard requirements (e.g. VDI/VDE 2634), a new artefact was designed by combining the advantages of both ball-cube and ball-bar artefacts [11]. Normally, balls to the rear side of a ball-cube are hidden from the measurement sensor.

By moving the ball from the back side to the interior of the artefact, this problem is resolved. This new spatial artefact is applicable for verifying single, as well as multiple-view optical-based area scanning systems. When comparing only three, in contrast to seven ball-bar measuring positions [12] with a single positioning of this spatial artefact, extensive time reductions in verification periods can be achieved. Because of the exposed position of the balls, the artefact can successfully replace a single–bar artefact and all the necessary multiple repositioning.

3.1 Design of the Artefact

The developed artefact has the geometric shape of an irregular tetrahedron. It consists of six tubes, three long and three short ones in a ratio of 2.3 : 1, and four ceramic spheres serving as probing elements (Fig. 3). Such design was chosen in order to have a spatial standard with a minimum number of probing elements, which can be scanned by an optical scanner in a single scan. The original idea was to have all four balls pointing out of the tetrahedron. However, after performing some virtual probing tests, it was decided to move one of the balls to the interior of the tetrahedron in order to enable the tested scanner to see all balls at the same time.

The artefact was constructed in two sizes. The height of the small artefact is 260 mm, while the height of the larger artefact is 1050 mm. The diameters of probing balls employed are 20 mm for the small artefact and 30 mm on the larger artefact. The main purpose of making the artefact in two different sizes was to enable the testing of different measurement ranges commonly available with commercial fringe projection measurement systems. The cameras on these systems can be set in various configurations and thus their metrological characteristics can change when operated over different measurement ranges. To support multi-scanning measurement systems, the artefact is additionally equipped with removable targets as shown on the right hand picture in Fig. 3.

Fig. 3. Small (left-hand picture) and large tetrahedron artefacts [11]

The tubes are constructed from composite materials consisting of carbon fibers in an epoxy matrix.

Ceramic spheres with lambertain surfaces, which offer desirable light scattering properties for optical systems, are glued on to stainless steel ball holders which also serve as joining elements between the tubes. These joints are attached to the composite tubes using epoxy glue and examples are shown in Fig. 4.

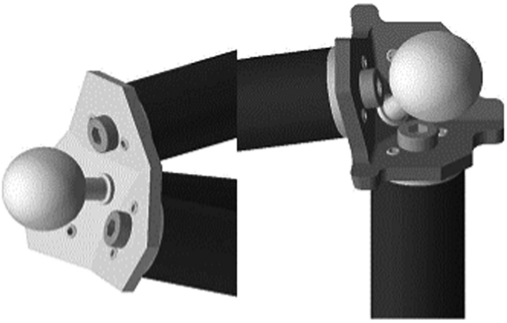

Fig. 4. Two details of the bar joint with a ball holder [11]

4 Calibration of the Artefact

4.1 Measurement Standards and Traceability

The artefact is being calibrated with the coordinate measuring machine (CMM) Zeiss UMC 850 [20]. The traceability of this machine is assured through periodic performance tests by using a set of long gauge blocks 125 mm to 500 mm. The standard is a link of the traceability chain presented in Fig. 7.

The standards are not calibrated periodically following a predefined calibration interval, but before each performance test in which they are used.

4.2 Calibration Procedure

Distances between the centres of the six corner ceramic spheres are measured by means of the ZEISS UMC 850 CMM. Distances between the spheres A-B, A-C and B-C have a nominal value of 506 mm, while distances between spheres A-D, B-D and C-D have a nominal value of 1060 mm.

Special stylus configuration is assembled for this calibration. The system consists of 4 styli, so that spheres can be reached from each direction. Figure 5 presents the example of the stylus system position for probing sphere C.

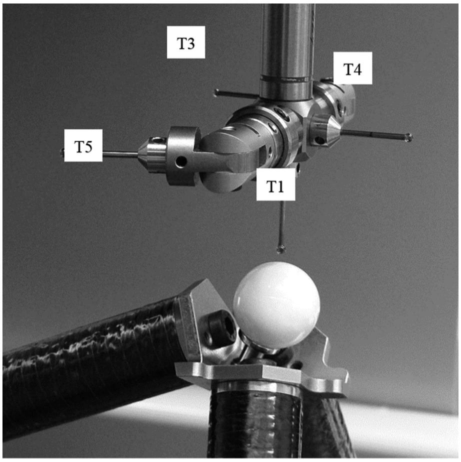

Fig. 5. Stylus system in sphere C position for probing

As indicated in Fig. 6, standard is laid on three prisms (40 × 35 × 120) mm^3, with steel corners glued to prisms, assuring tension-free fixation. Spheres are reachable for styli from all directions.

Each ball is probed in 25 points (5 groups of 5 probing points). Standard's coordinate system shall be put in the centre of the sphere A (bottom left corner, Fig. 11). Spatial rotation is carried out on the plane through centres of spheres A, B and C. Planar rotation is performed around the line through the centres of spheres A and B.

Measurements of the distances between sphere centres are carried out five times and arithmetical mean of altogether six distances (A-B, A-C, B-C, A-D, B-D, and C-D) between sphere centres is calculated.

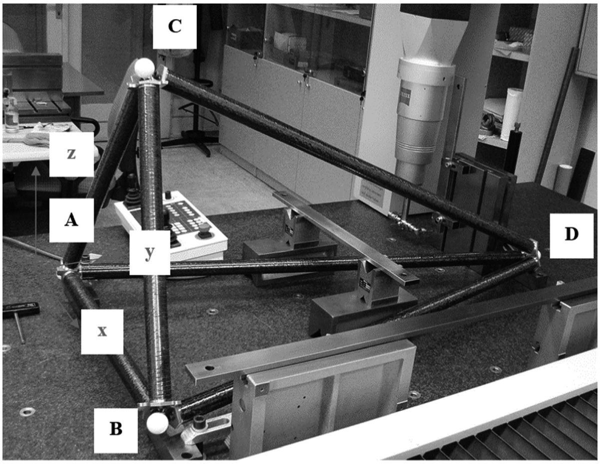

Fig. 6. Position of the bigger standard in the measuring volume

Calibration uncertainty representing best calibration and measurement capability (CMC) is equal to the uncertainty of the CMM performance test and is:

$$U = 3,2\,\mu\mathrm{m} + 5,0 \cdot 10^{-6} \cdot L, k = 2 \tag{1}$$

where:
U - expanded measurement uncertainty at a level of confidence $\approx 95\%$
L - measured length
k - coverage factor.

5 Performance Test of a Fringe Projection System by Using the Tetrahedron Standard

The procedure [11, 21] developed in the Laboratory for Production Measurement in the frame of the EU metrology project iMERA Plus JRP T3.J2.2 NIMTech, is applicable for testing optical measurement machines for quality parameter "length measurement error" in one or more images. It is suitable for testing fringe projection and photogrammetric measurement systems.

5.1 Measurement Standards and Traceability

Tetrahedron measurement standards described in Chapter 3 are used for the performance test. Ceramic spheres have a diameter of 20 mm (small standard) resp. 30 mm (large standard) and diffusely scattering surface. Roughness of the spheres is negligibly small in comparison with the requested precision of the test. Large standard is additionally equipped with four mark plates (see Fig. 3) in order to allow performance testing in multiple scan mode. The standard balls are well visible by all optical instruments, spraying is not necessary.

The standards are calibrated by using a tactile CMM, while the CMM is calibrated in our laboratory by using gauge clocks of dimensions 125 mm to 500 mm. The traceability chain with corresponding measurement uncertainties in all calibration stages is presented in Fig. 7.

5.2 Test Procedure – Single Scan

Small standard (see Sect. 3.1) is normally selected for measurement ranges from (100 × 100 × 100) mm^3 to (500 × 500 × 500) mm^3. However, it can also be used for bigger ranges, if the customer wants to check accuracy within smaller portions of the measurement range. For ranges above (500 × 500 × 500) mm^3 we normally select the bigger standard.

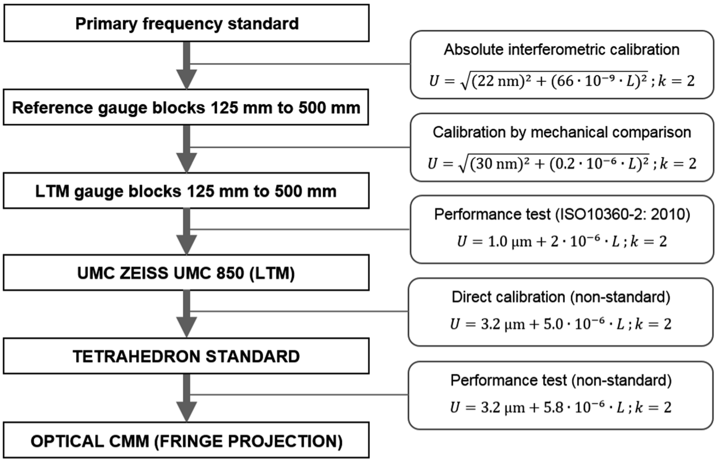

Fig. 7. Traceability chain for the performance test of a fringe projection systems

The standard shall be placed in accordance with the sketches in Fig. 10, as follows:

- The standard should face the camera with the bar AB comprising angle in vertical projection of approx. 15° to the optical axis of the camera.
- Focus of the camera should be in the centre of the standard.
- Camera should comprise a vertical angle of approx. 40°.

The standard should be scanned accordingly to machine's standard procedure. Therefore, a machine operator is required to be present at the test (Fig. 8).

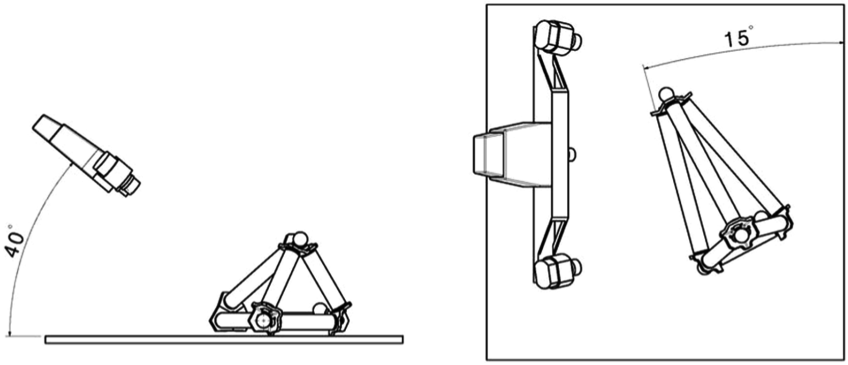

Fig. 8. Position of the standard [11, 21]

Primitives (spheres) should be evaluated by using Best-Fit Sphere procedure with $1-\sigma$ deviation from ideal geometric primitive. Six Point to Point distances between all spheres centres (AB, AC, AD, BC, BD, CD) are to be measured.

5.3 Test Procedure – Multiple Scan

For measurements with more images, large standard (with mark plates) is to be used. The number of images is determined by including all distances between spheres in the measurement. Standard is positioned according to exact instructions in the procedure. Normally, two or three different positions are applied. Primitives (spheres) should be evaluated in the same way as in the single scan procedure.

Measurement results are to be compared with calibrated values of distances between sphere centres.

In accordance with EN ISO 10360-2 [3], the limiting value of the length measurement error MPEE is stated either as a length-dependent quantity $\pm(A + L/K)$, as a maximum value $\pm B$, or as a combination of the two. It must be complied with over the whole measuring volume of the optical 3D measuring system and under all admissible conditions of measurement. For the limiting value for the length measurement error to be completely stated, the operating and ambient conditions referred to must also be given.

When comparing the length measurement error E with its limits MPEE, the expanded uncertainty of measurement U of the test method is also to be taken into account:

$$|E| \leq |\mathrm{MPEE}| - U \text{ for the manufacturer} \tag{2}$$

$$|E| \leq |\mathrm{MPEE}| + U \,\text{for the customer} \tag{3}$$

The quality parameter length measurement error is complied with if – taking account of the uncertainty of measurement – no length measurement error exceeds the limit for the maximum permissible length measurement error MPEE as regards its amount. If this limiting value is exceeded maximally once, the measurement in which the limit has been exceeded must be repeated three times. In these repeat measurements the limit must not be exceeded again. Otherwise, the acceptance test is not successful.

The limit for the quality parameter is to be complied with under all conditions permitted by the manufacturer. This applies in particular with regard to the surface properties of the artefacts and the filter parameters.

5.4 Measurement Uncertainty

Mathematical Model of Measurement. Mathematical model of measurement for the presented calibration (test) task can be expressed as follows:

$$e = L_{\mathrm{om}} - L_{\mathrm{m}} \cdot (1 + \alpha_{\mathrm{m}} \cdot \theta_{\mathrm{m}}) \tag{4}$$

where:
e - deviation (measurement result) at 20 °C
L_{om} - length reading on the optical measurement machine
L_{m} - length of the standard
α_{m} - linear temperature expansion coefficient of the standard
θ_{m} - temperature deviation of the standard from 20 °C

Standard Uncertainties of the Input Value Estimates and Combined Standard Uncertainty of Measurement. Combined standard uncertainty [21–25] is expressed with the uncertainties of the input values by the following equation:

$$u_c^2(e) = c_{\mathrm{Lom}}^2 u^2(L_{\mathrm{om}}) + c_{\mathrm{Lm}}^2 u^2(L_{\mathrm{m}}) + c_{\alpha\mathrm{m}}^2 u^2(\alpha_{\mathrm{m}}) + c_{\theta\mathrm{m}}^2 u^2(\theta_{\mathrm{m}}) \tag{5}$$

where c_{i} are partial derivatives of the function (4):

$$c_{\mathrm{Lom}} = \partial \mathrm{f}/\partial L_{\mathrm{om}} = 1 \tag{6}$$

$$c_{\mathrm{Lm}} = \partial \mathrm{f}/\partial L_{\mathrm{m}} = -(1 + \alpha_{\mathrm{m}} \cdot \theta_{\mathrm{m}}) \approx -1 \,\text{at}\, \theta_{\mathrm{mmax}} = \pm 1\,^{\circ}\mathrm{C} \tag{7}$$

$$c_{\alpha\mathrm{m}} = \partial \mathrm{f}/\partial \alpha_{\mathrm{m}} = -\theta_{\mathrm{m}} \cdot L_{\mathrm{m}} \tag{8}$$

$$c_{\theta\mathrm{m}} = \partial \mathrm{f}/\partial \theta_{\mathrm{e}} = -\alpha_{\mathrm{m}} \cdot L_{\mathrm{m}} \tag{9}$$

Standard uncertainties of influence (input) values are calculated (estimated) for applied equipment and method as well as for supposed measurement conditions (Table 1).

(a) *Uncertainty of optical measurement machine reading* $u(L_{\mathrm{om}})$

Uncertainty of optical measurement machine reading consists of uncertainty due to rounding the measured value, and uncertainty due to of repeatability of the measurement.

- Optical measurement machine's resolution of 0,01 mm causes the error interval of ±5 μm (due to rounding). With the rectangular distribution, standard uncertainty of machine's reading is:

$$u(L_{\mathrm{L}}) = (5\,\mu\mathrm{m})\Big/\sqrt{3} = 2,2\,\mu\mathrm{m}$$

For resolution 0,0001 mm, $u(L_{\mathrm{L}})$ = 0,3 μm.

- Repeatability of measurement has to be established during the calibration by measuring the distance AC five times. Average distance is calculated, as well as deviations e and average deviation $\bar{e}$.
- Standard uncertainty of measurement machine reading $u(L_{\mathrm{om}})$ is:

$$u(L_{\mathrm{om}}) = \sqrt{u(L_{\mathrm{L}})^2 + (\bar{e}/\sqrt{3})^2} \tag{10}$$

(b) *Uncertainty of the standard's length* $u(L_{\mathrm{m}})$

According to calibration certificate, uncertainty of the standard's length is:

$$u(L_{\mathrm{m}}) = 1,6\ \mu\mathrm{m} + 2,5 \cdot 10^{-6} \cdot L \tag{11}$$

(c) *Uncertainty of the standard's linear temperature expansion coefficient* $u(\alpha_{\mathrm{m}})$

Standard's linear temperature expansion coefficient, as established by extensive tests, is $2,2 \cdot 10^{-6}\ {}^{\circ}\mathrm{C}^{-1}$, interval of $\pm 1 \cdot 10^{-6}\ {}^{\circ}\mathrm{C}^{-1}$ is estimated. Standard uncertainty at supposed rectangular distribution is:

$$u(\alpha_m) = (1 \cdot 10^{-6}\,{}^{\circ}\mathrm{C}^{-1})/\sqrt{3} = 0,58 \cdot 10^{-6}\,{}^{\circ}\mathrm{C}^{-1}$$

(d) *Uncertainty of the standard*'s temperature deviation u(θ_m)

Temperature deviations are estimated to be ±1 °C. Standard uncertainty at assumed rectangular distribution is:

$$u(\theta_{\mathrm{m}}) = 0,58\,^{\circ}\mathrm{C}$$

Table 1. Uncertainty budget in optical CMM performance test

Value X_i	Standard uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution
L_{om}	(to be calc.)	Rectangular	1	(to be calc.)
L_m	1,6 µm + 2, $5 \cdot 10^{-6} \cdot L$	Rectangular	−1	1,6 µm + 2, $5 \cdot 10^{-6} \cdot L$
α_m	$0{,}58 \cdot 10^{-6}$ °C^{-1}	Rectangular	1 °C·L	$0{,}58 \cdot 10^{-6} \cdot L$
θ_m	0,58 °C	Rectangular	$2{,}2 \cdot 10^{-6}$ °C$^{-1} \cdot L$	$1{,}3 \cdot 10^{-6} \cdot L$
		Total: $\sqrt{(\sqrt{(1,6\,\mu\mathrm{m})^2 + u(L_{\mathrm{om}})^2})^2 + (2,9 \cdot 10^{-6} \cdot L)^2}$		

For the CMC calculation, supposed resolution of the optical measurement machine is 0, 1 µm and the repeatability of 5 consecutive measurements is 0. CMC (expanded measurement uncertainty with the level of confidence 95%) is then:

$$U = 3,2\,\mu\mathrm{m} + 5,8 \cdot 10^{6} \cdot L; k = 2 \qquad (12)$$

6 Conclusions

In order to assist optical 3D metrology requirement, our laboratory joined the consortium of the iMERA Plus JRP T3.J2.2 NIMTech project, within which we have developed and presented a number of verification artefacts for different traceability purposes. The presented tetrahedron standards offer quicker solution for performance testing of optical 3D instruments compared with currently available standards. Its design is based on an extensive study of metrology tasks of 3D optical devices, such as sheet forming tools, sheet parts, freeform pipes (exhaust systems, …), housings of home appliances, car bodies etc. and is therefore suited for efficient evaluation of performing single scan and multiple scan tasks. Further investigations will be focused into the long–term stability and the sensitivity of the artefacts when used in harsh environmental conditions. Also some new materials with lower mass, better surface properties and even better stability should be examined as well. Improved designs based on experiences through application are also expected. The calibration and verification test procedures have already been developed, but should be subject to further investigation and development.

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