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Verification of an articulated arm coordinate measuring machine using a laser tracker as reference equipment and an indexed metrology platform.

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In this work the analysis of the use of a laser tracker as a reference instrument in calibration and verification procedures for articulated arm coordinate measuring machines (AACMM) with an indexed metrology platform is presented. In the case of AACMM verification procedures, where it is necessary to evaluate its maximum working volume, this technique represents an alternative to conventional one-dimensional gauges and avoids the need of materializing the lengths required for a conventional gauge by increasing the flexibility for defining test positions and broadening the definition of reference test lengths depending on equipment calibration or verification requirements. First a procedure for the AACMM verification with the indexed metrology platform (IMP) and the laser tracker (LT) used as a reference instrument was defined and the required accuracy of the equipment was assessed. The experimental testing to validate its proper application was carried out by means of laser tracker measurements of six retroreflector targets located in a mesh that simulated the AACMM working volume. Finally, the results obtained with both equipment, laser tracker and AACMM with indexed metrology platform, showed that the procedure presented is suitable and that the laser tracker could be considered as a reference instrument for AACMM verification processes when the nominal accuracy of the laser tracker is assured.

1. Introduction

Calibration and verification processes for portable measuring instruments require calibrated gauges to establish the reference dimensions which will be used to calculate the errors of the measuring process. In regard to articulated arm coordinate measuring machines (AACMMs), its usage comes from the verification processes of coordinate measuring machines (CMMs) where the verification is carried out by measuring gauges which materialize the dimensions to be quantified. One-dimensional, two-dimensional or three-dimensional gauges are commonly employed in these types of procedures. Gauges that could materialize more than one dimension allow reducing the number of positions of the gauge within the CMM verification procedures which results in the reduction of testing time and cost.

In regard to AACMM it is required to evaluate most of its working volume throughout the verification process, which makes one-dimensional gauges appropriate for this type of procedures, mostly due to its easy movement around the measuring equipment that allows to settle the testing positions according to the applicable evaluation norms [1], [2] and [3]. Examples of this type of gauges are ball bars which materialize distances between spheres. They are extensively used in AACMM calibration and verification procedures due to its flexibility, high precision, low cost and easy use concept in comparison with other gauge types [4,5]. Verification standards [1–3] used this type of gauges in their specified testing protocols. Kovac and Frank [6] developed a new high precision measuring device for AACMM testing and calibration based on laser interferometer measurements along a line gauge beam. Santolaria et al. [5,7–10] reported a method to calibrate an AACMM based on the Denavit-Hartenberg kinematic model parameters [11]. These parameters are optimized measuring a calibrated ball bar gauge located at different orientations and positions of the AACMM working volume. In [12] the authors developed a metrological model to identify the kinematical parameters of a measuring arm as well as the errors associated with its measurements and in [13] was established an online simulation system called virtual articulated arm coordinate measuring machine, which allows the evaluation of measurements' accuracy as well as the determination of the compensation matrix using ball bar gauges. Regarding tridimensional gauges, Shimojima et al. [14] presented a method to estimate the uncertainty of an AACMM, involving the use of a three dimensional ball plate gauge with nine balls which is oriented in five different positions. As a result the kinematical parameters of each joint were determined. A similar approach for tridimensional gauges is shown in [15].

The use of kinematic seats in AACMM's calibration procedures is extended and shows advantages in comparison with other gauges as presented in [16], where kinematic seats are used for estimating the repeatability of the arm. In [17] it is proposed a solid plate composed of kinematic seats as gauge for AACMM's calibration. Piratelli [18] introduces the development of virtual geometry gauges, virtual ball bar, to evaluate the performance of AACMMs. The proposed gauge has two groups of four holes each that are used to determine points of the spherical surfaces. These points are fitted to spheres using computational algorithms and the distances between spheres centers are calculated and compared to the calibrated length. In further works of the same author [19], a virtual sphere plate gauge is developed defining 16 groups of four conic holes placed on aluminum pyramidal blocks. These groups determine 16 virtual spheres by taking points in each conic hole with a CMM rigid probe and a spherical stylus on the arm extremity. Performance test according to ASME B89.4.22, 2004 are carried out and the uncertainty of the virtual sphere plate is calculated. As mentioned in [18] the virtual sphere concept is applied in order to reduce the number of test positions specified in the standards [1], [2] and [3] and increase the efficiency of the verification procedure for AACMM. Another approach to this concept using a virtual circle instead of virtual spheres as proposed in [18] for AACMMs evaluation, is done by Gonzalez et al. [20], [21]. They present a virtual circle gauge method composed of two aluminium alloy bar gauges of 1000 mm length with four groups of three conic holes which determine the four virtual circles. The same author in [22] analyzes the influence of the contact force applied by the operator on the performance of AACMMs by means of a contact force sensor and a ring gauge, proposing a probe deflection model to reduce the diameter error. AACMMs are manually operated, fact that allows that a same point could be measured from multiple arm's poses. This is a big advantage but it consequently makes AACMM's repeatability and accuracy to be lower than in CMMs. In relation to this point and in order to identified accurately the metrological characteristics of an AACMM, Cuesta et al. [23], develop a novel gauge for AACMM's verification and calibration which includes multiple geometries in the same gauge, manufactured conic holes on each gauge sides that will allow the measurement of distances between centers and diameters of the virtual spheres defined by the conic holes.

Nevertheless, the physical nature of the gauge itself imposes limitations on the number of distances to be materialized within the tests, due to the reason that the number of test lengths is restricted to the gauge length or to the distance combinations between gauge sphere centers. On these grounds, sometimes several gauges should be used in the same testing procedure to increase the number of test lengths.

In order to develop new gauges and alternative calibration and verification techniques applied to AACMM, in this work the analysis of the use of a laser tracker as a reference instrument in the calibration and verification procedures of AACMM replacing the conventional one-dimensional gauges as ball bars is presented. This technique avoids the need of materializing the length required in a conventional gauge, increasing the flexibility for defining test positions and broadens the definition of reference lengths depending on equipment calibration or verification requirements.

The first developments of measurement based on laser tracker applied to accuracy analysis for robots dates back to the 1980's [24], [25], [26]. But recently the dimensional verification for large range structures in automation or aeronautic sectors [27] has pushed forward and laser tracker technology has grown substantially over the last 20 years. The need for improving current dimensional verification techniques available for large volume parts and for machine tool calibration and verification [28] has led to the evolution of large scale non-contact measuring equipment as laser trackers or lacer tracers. The laser tracker is a large scale portable measuring instrument with high accuracy that measures the position of an object in spherical coordinates. It uses interferometry for measuring relative distances and optical encoders for azimuth and elevation angles of a beam steering mirror. A laser tracker is composed of the following components: laser source, a beam steering mechanism with angular encoders, interferometer, position sensor detector (PSD), beam splitting optics, a retroreflector and a control unit. These components are used to track the target, typically an spherically mounted retroreflector (SMR) and measure its center x, y and z coordinates. Its working principle [29,30] is based on a source beam emitted by the interferometer which is divided into two by the beam splitting optics. The measurement beam travels from this beam splitter to the target and comes back, then it interferes with the reference of the original beam and this interference will be used to determine the change in displacement of the target. Extensive literature regarding the application of laser trackers for CMMs evaluation and calibration of its geometrical errors has been identified. The use of this equipment could avoid some of the drawbacks of artifacts such as step gauges or ball plates. In [31] is reported a high precision laser tracker for CMM calibration that takes advantage of its tracking system based on a hemisphere to reach measurement uncertainties below 0.3 μm. In [32] it is also described the use of a laser tracker for CMM calibration with a small residual and an standard deviation of 1 μm when comparing the parametric errors estimated by the laser tracking system to raw data measured by the ball plate method. The authors in [33] show how to map a CMM with a laser tracer resulting in uncertainties in the range of 1 μm.

For the purpose of this work, several spherically mounted retroreflectors (SMRs) are positioned as targets in a mesh and their distance between centers will materialize the reference length to be measured by the laser tracker. This reference length will be defined as the calibrated length. However, it is important to point out that one of the factors to be taken into consideration in this analysis, will be the fact that high range measuring equipment as laser trackers, may not have the required accuracy for AACMM calibration and verification procedures.

2. Laser tracker accuracy evaluation

Product specifications of commercial laser trackers from representative manufacturers, show angular accuracy around 20 μm + 5 μm/m, distance accuracy with absolute distance measurement (ADM) of 16 μm + 0.8 μm/m and approximately 4 μm + 0.8 μm/m as a value of distance accuracy in measurements with interferometer as shown in Table 1:

Table 1. Commercial laser trackers product specifications

Model	Working range(m)	Angular accuracy	Distance accuracy (ADM)	Distance accuracy (IFM)
Leica LTD600	40	±25µm	± 25 µm	± 10 µm ± 0.5 µm/m
Leica AT401	320	15µm+6µm/m	±10µm	±0.4µm
Leica AT901	50/160	15µm+6µm/m	±10µm	+0.3µm/m
Faro Ion	30/40/55	20µm+5µm/m	16µm+0.8µm/m	4µm+0.8µm/m
Faro Vantage	30/60/80	20µm+5µm/m	16µm+0.8µm/m	
Api Tracker3	15/40/60	3.5µm/m	±15µm (1.5ppm)	>±0.5ppm
Api Radian	40/100/160	3.5µm/m	±10µm (1ppm)	>±0.5ppm
Api Omni 2	160/200	±18+5ppm	±15µm +1.5µm/m	

The LT model used in the experimental testing is a Leica LTD600 with angular accuracy of ± 25 µm for distances below 2.5 m and fixed target, ADM accuracy of ± 25 µm and IFM accuracy of ± 10 µm ± 0.5 µm/m. As it could be seen in Table 1, current commercial laser trackers offer better distance accuracy which would be valid enough for measurements in short distances, below 2 m, and could be used in calibration processes of AACMMs with volumetric accuracy over 50 µm approximately, if we take as a reference the values offered in commercial AACMM and a laser tracker distance accuracy (IFM) of 4 µm + 0.8 µm/m as shown in Table 1.

In order to assess the equipment's accuracy specifications submitted by the manufacturers listed in Table 1 and to validate its proper use as reference equipment in calibration processes for AACMMs, experimental tests with the laser tracker Leica LTD600 were also carried out in this work.

2.1. Evaluation test in machine tool

Firstly, distance measurements between 0 and 500 mm, back and forth in a machine tool, were conducted by means of the interferometer. Simultaneously, the SMR center coordinates were captured in all the positions (0 - 500mm) and the Euclidean distance between two SMR centers measured in all positions were calculated and compared with the interferometer distance values.

The objective of the experimental test was to verify the measurement error of the laser tracker in short distances versus the measurements attained with the interferometer. This equipment, due to its higher accuracy, was considered as the reference equipment and its measurements as nominal data. The test set up is shown is Fig. 1 with the Leica LTD600 laser tracker on the left side and the interferometer on the right side of the picture.

Fig. 1 Positioning of laser tracker and interferometer in the experimental test set up in machine tool

In Table 2 the values obtained in the test with both measuring equipment, laser tracker and interferometer are listed:

Table 2. Distance measurements in machine tool with laser tracker and interferometer

Interferometer			Laser tracker		
Nominal (mm)	Back (mm)	Forth(mm)	Nominal (mm)	Back (mm)	Forth(mm)
0	0.002	0.025	0	0.000	0.030
-50	-50.002	-49.976	50	49.998	49.974
-100	-100.000	-99.975	100	99.993	99.971
-150	-149.999	-149.971	150	149.990	149.965
-200	-200.000	-199.972	200	199.995	199.969
-250	-250.005	-249.981	250	250.000	249.972
-300	-300.011	-299.981	300	300.005	299.979
-350	-350.018	-349.995	350	350.012	349.990
-400	-400.025	-400.002	400	400.022	399.995
-450	-450.043	-450.013	450	450.037	450.006
-500	-500.045	-500.017	500	500.040	500.009

The distance errors, assuming the interferometer measurements as nominal values are included in Table 3, being the mean errors ± 0.005 mm and ± 0.005 mm for the back and forth series in the machine tool respectively. The maximum error values obtained are 0.009 mm and 0.009 mm.

Table 3. Laser tracker and interferometer test in machine tool measurement results

$Li_{LT} – Li_{IFM}$ Back (mm)	$Li_{LT} - Li_{IFM}$ Back (abs mm)	$Li_{LT} - Li_{IFM}$ Forth (mm)	$Li_{LT} - Li_{IFM}$ Forth (abs mm)
-0.002	0.002	0.005	0.005
-0.004	0.004	-0.002	0.002
-0.007	0.007	-0.004	0.004
-0.009	0.009	-0.006	0.006
-0.005	0.005	-0.003	0.003
-0.005	0.005	-0.009	0.009
-0.006	0.006	-0.002	0.002
-0.006	0.006	-0.005	0.005
-0.003	0.003	-0.007	0.007
-0.006	0.006	-0.007	0.007
-0.005	0.005	-0.008	0.008
Mean error (mm)	0.005		0.005
Maximum error (mm)	0.009		0.009

2.2. Evaluation test on a linear guide

In a second step, a test series on a linear guide was performed using an interferometer again as reference equipment and calculating the distance values. Simultaneously to the interferometer measurements, the SMR center coordinates were captured in all the positions (0-1200mm) and the Euclidean distance between two SMR centers measured in each test positions was calculated and compared with the interferometer distance value obtained.

The laser tracker and the interferometer were placed one on each side of the linear guide, which was positioned in a radial disposition in order to minimize the tilt of the interferometer's head. The details of the test set up are shown in Fig. 2:

Fig. 2 Laser tracker and interferometer on linear guide experimental test set up

The distance range verified was between 0 and 1200 mm and the distance values measured with the interferometer and the laser tracker are shown in Table 4. In addition the distance error $Li_{LT} – Li_{IFM}$ for the laser tracker was calculated considering the interferometer values as nominal ones in this process.

Table 4. Laser tracker and interferometer test on linear guide measurement results

	IFM (mm)	Laser tracker (mm)	$Li_{LT} - Li_{IFM}$ (mm)	$Li_{LT} - Li_{IFM}$ (abs mm)
1	0.000	0.000	0.000	0.000
2	56.439	56.448	0.009	0.009
3	106.408	106.409	0.001	0.001
4	156.522	156.522	0.001	0.001
5	206.451	206.445	-0.006	0.006
6	256.453	256.456	0.003	0.003
7	306.389	306.394	0.005	0.005
8	356.520	356.527	0.007	0.007
9	406.385	406.383	-0.003	0.003
10	456.375	456.375	0.000	0.000
11	506.055	506.051	-0.004	0.004
12	606.358	606.352	-0.006	0.006
13	655.991	655.996	0.005	0.005
14	706.237	706.243	0.007	0.007
15	756.295	756.299	0.004	0.004
16	806.249	806.256	0.007	0.007
17	856.224	856.229	0.005	0.005
18	906.277	906.285	0.008	0.008
19	956.249	956.252	0.003	0.003
20	1006.240	1006.250	0.010	0.010
21	1056.275	1056.281	0.006	0.006
22	1106.247	1106.250	0.003	0.003
23	1156.232	1156.227	-0.005	0.005
24	1206.231	1206.243	0.012	0.012
Mean error (mm)				0.005
Maximum error (mm)				0.012

The mean and maximum distance errors values calculated for the laser tracker were ± 0.005 mm and 0.012 mm respectively. Both figures are quite similar to the ones obtained in the first test in the machine tool with the same laser tracker and interferometer. In that case, the mean and maximum

distance errors on the back series, were very close to the forth series, ± 0.005 mm and 0.009 mm respectively. The mean distance error value ± 0.005 mm obtained in the tests for the laser tracker in case of test lengths below 1200 mm, validates its use as a reference instrument in the verification procedures for AACMMs with measurement accuracy beyond 50 µm.
On this premise the reference instrument, laser tracker in this case, will have an accuracy with one order of magnitude over the AACMM to be calibrated or verified. Furthermore, it is proved with these tests that the real accuracy of the laser tracker obtained in the experimental procedure, ± 0.005 mm, is better than the one specified by the manufacturer in the product specification for the model Leica LTD600D, ± 10 µm ±0.5 µm/m, corresponding to an accuracy of ± 10.6 µm for a 1.2 m length.
A proposal for fixing the lack of accuracy of laser trackers that is required for AACMM's calibration is the use of multiple laser trackers through multilateration [34], [10]. This technique enables a decrease in the measurement uncertainty by means of angular noise reduction. Therefore, the points captured by the laser trackers with this multilateration technique could be considered as nominal values in the calibration procedure of the AACMM. Multilateration is defined by [35] as a measuring system that determines either two or three dimensional coordinates by combining only length measurements made from fixed points. In [36] the author shows the first novel coordinate measurement using the trilateration principal where the placement of the laser tracker is arbitrary. The optimal arrangement of the laser tracker stations and measurement volume are introduced by [37] and [38]. In [39] a new multilateration set up for high precision calibration of small artefacts was defined and recommendations for optimization of multilateration set ups and measurement plans and for minimizing measurement uncertainty are presented. Hughes et al. [40] developed a laser-interferometry measuring station with a target uncertainty of 300 nm based on the principle of multilateration whereby spatial coordinates are determined from measurements of displacement of four targets relative to eight measuring stations.

3. Experimental procedure

In this work the equipment used during the experimental phase were the following: a laser tracker Leica LTD600, an articulated arm coordinate measuring machine Faro arm Platinum with a diameter measuring volume of 2.4 meters and a 2-2-3 measuring configuration type, an indexed metrology platform (IMP) and six spherically mounted retroreflectors (SMRs) model Hallow 40M with diameter 1.5" (38.1 mm) and sphere roundness grade 50 ± 0.00005" (±1.3 µm). The six SMRs were distributed within a mesh whose area represents the measuring working volume of the AACMM and corresponds to a 60º angle turned by the IMP when changing from one position to the following.
The positioning of the SMRs into six different locations was made according to the height where the SMR is placed (low, medium, high) corresponding the lowest height to the ground, and the distance from the SMR to the AACMM's working volume center, which was classified as near and far. Table 5 shows the six different locations of the SMRs. The test set up including the laser tracker, AACMM, indexed metrology platform and SMRs mesh is shown in Fig. 3.

Table 5. Definition of SMR locations in the test

SMR number	Height	Distance to the AACMM
1	High	Far
2	Medium	Far
3	Low	Far
4	High	Near
5	Medium	Near
6	Low	Near

Fig. 3 Positioning of SMRs, AACMM and laser tracker in experimental test set up

Firstly, we carried out the calibration of the AACMM with a kinematic seat and a 6 mm diameter ceramic probe. The maximum error and standard deviation values obtained in the calibration were 0.072 mm and 0.0295 mm respectively.

3.1. AACMM verification procedure with the indexed metrology platform IMP

The use of an indexed metrology platform (IMP) is evaluated in this work as an alternative method to evaluate the volumetric accuracy and repeatability of AACMMs. Brau et al. [41], proposed the use of this platform whose main advantage resides in the reduction of the time and physical effort required to carry out these type of procedures, by fixing the calibrated gauge object and placing the AACMM on the IMP upper platform throughout the verification procedure.
The IMP is composed of two hexagonal platforms, one fixed lower platform and a mobile upper platform which rotates around the fixed one every 60º allowing the definition of six different positions, see Fig. 4. The mechanical repeatability of the platform, 0.7 µm, is achieved by means of kinematic couplings configuration of spheres and cylinders. Three reference spheres located on each platform, allows the determination of the reference systems of both platforms and the possibility to express the coordinates of a captured point by the AACMM in the fixed lower platform global coordinate system during verification procedures. The IMP has also a high mechanical position repeatability, 4 µm, fact that allows to measure with high precision the orientation and position of the upper platform with respect to the lower platform, Brau et al. [41]. This feature is accomplished with the use of six capacitive sensors with nanometer resolution and measuring range of 100 µm for an output voltage from 10 to - 10 V and an operational range from 100 to 200 µm with their sensors and targets assembled in the upper and lower platforms respectively. The

coordinates of the AACMM's captured points in the verification procedure are obtained in a fixed global coordinate system located in the lower platform of the IMP. By means of a mathematical model explained in Brau et al. [41] a homogenous transformation matrix (HTM) is found allowing the change of coordinate systems required.

The use of the IMP shows a clear testing time and man efforts reduction up to 75% in comparison with conventional verification procedures. In this case the portable measuring instrument placed on the IMP, rotates jointly with the upper platform during the verification procedure, enabling a great coverage of the AACMM working volume and the definition of a broad number of testing positions but avoiding the movement of the calibrate gauge object during the verification. Moreover, not only testing and set up times are reduced with the use of the IMP, but also the space needed in the data capturing process is diminished since the number of physical testing positions of the gauge are minimized.

Fig. 4 Indexed metrology platform IMP rotating positions and example of test set up with IMP.

3.2. AACMM performance test

The experimental procedure starts with the measurement of the SMRs with the laser tracker where the firm magnetic fixing used makes it possible to increase the number of data per point up to 500. Beginning with position 1 and according to Table 5 we measured with the laser tracker all the SMRs located in the six different locations capturing the SMR's center coordinates. The measurements were carried out with IFM and aligning the laser tracker in order to minimize the laser tracker head rotation trying to reproduce the validation tests carried out with the laser tracker described in the section 2. The center data along with the SMR's diameter and the euclidean distance between the centers will be considered as the calibrated values in the verification procedure of the AACMM. The positioning of the SMRs in the mesh taken as reference from the measurements made with the laser tracker is shown in Fig. 5 (a).

After measuring the SMRs with the laser tracker, we measured the SMRs with the AACMM. First of all, we measured the three reference spheres located in the mobile IMP upper platform. Hence, the homogeneous transformation matrix (HTM) that links the AACMM's coordinate reference system and the mobile upper platform's reference system was calculated. Simultaneously to the AACMM measurement, the capacitive sensors readings are saved. These values will allow the calculation of the global coordinate reference system transformation matrix from the upper platform to the lower platform of the IMP. Afterwards and for each position of the IMP (1-6), the measurement of the six SMRs located in the six fixed locations is carried out, not moving the SMRs from their original location in the laser tracker measurement process. The location of the SMRs in the mesh for each of the six positions of the IMP, according to the AACMM's measurement with the SMRs' center coordinates expressed in the fixed lower platform reference system (global reference system) are shown in Fig. 5(b) and Fig. 5(c) respectively.

All the tests were carried out twice in order to foresee the influence of the operator in the AACMM's measuring process. Fig. 5(b) represents the measurements of the operator 1 and Fig. 5(c) of the operator 2.

Fig. 5 SMRs positioning in the mesh according to laser tracker (5a) and AACMM measurement with Operator 1 (5b) / Operator 2 (5c) for IMP positions (1-6)

Once all the SMRs are measured with the laser tracker and the AACMM, the values obtained are compared and the error calculation is estimated in two different ways.

First, an evaluation of the AACMM accuracy in terms of size test was carried out. This evaluation is similar to the probing error of the size test specified in the guidelines and standard [3], [2] and [1] in which the diameter of the SMR is measured. The calibrated reference values was the nominal diameter of the SMR given by the manufacturer, 1.5" (38,1 mm) and the largest deviation from the SMR calibrated value is reported as maximum deviation (d_i-d_{Cal}), being d_i the diameter of the SMR measured by the AACMM and d_{Cal} the calibrated diameter.

Second, a calculation of the distance error which shows the volumetric accuracy of the AACMM in all its working volume was performed. In this way, the distance between the centers of any two SMRs measured with the laser tracker (L_{Cal}) and with the AACMM (L_i) is calculated. Then the distance error Di, will be the difference between L_i and L_{Cal}, where the value measured with the laser tracker is considered as reference in this analysis as stated in Eq. (1).

$$Di = Li - L_{Cal} \quad (1)$$

In this work, we calculated 15 distances between the six SMRs' centers, as seen in Table 6:

Table 6. Distance between SMRs centers matrix

SMR Origin	SMR1	SMR2	SMR3	SMR4	SMR5
Distances	1-2	2-3	3-4	4-5	5-6
	1-3	2-4	3-5	4-6	
	1-4	2-5	3-6		
	1-5	2-6			
	1-6				

As a final result of this test, three parameters are obtained, the maximum distance deviation among tests positions Max Di (L_i – L_{Cal}), the range of the distance deviations and a mean deviation 2RMS calculated as twice the root mean square of the deviations out of all the test positions, see Eq. (2).

$$2RMS=2\ ((\sum(Di^2\ )/n)^{1/2})\ \ \text{with } n=6 \tag{2}$$

4. Results

The results obtained in the experimental tests allow us to evaluate the suitability of a laser tracker for AACMM calibration and verification procedures. As mentioned in chapter 3, first we carried out the evaluation of the probing error for the size test, defined as the difference between the diameters measured by the AACMM d_i and the nominal d_{Cal} 1.5” (38.1 mm). Second, the evaluation of the AACMM’s distance error by means of a volumetric performance test is performed. Thus, the distance between the centers of any of two SMRs measured with the laser tracker and with the AACMM is obtained. The distance error Di will be calculated as the difference of the distance between SMRs’ centers measured with the arm L_i and the distance between the centers measured with the laser tracker L_{Cal}. 15 euclidean distances between the centers of the SMRs are calculated and the nominal values obtained with the laser tracker are shown in Table 7.

Table 7. Calibrated lengths between SMRs centers measured with laser tracker

Distances (mm) – Calibrated length					
SMR		SMR		SMR	
1-2	523.8045	2-3	775.0102	3-5	1016.9956
1-3	1286.0485	2-4	927.2232	3-6	1490.7376
1-4	1182.3727	2-5	496.1383	4-5	691.9169
1-5	512.0332	2-6	825.0015	4-6	1124.4904
1-6	427.8762	3-4	864.5993	5-6	493.8272

4.1. Probing error of the size test results

As mentioned before, we want to evaluate with this test the error of the AACMM in the measurement of one dimension, diameter of the SMR in this case, comparing with its nominal value 1.5” (38.1 mm).
According to the manufacturer specification, the SMR has a sphere roundness grade of 50 ± 0.00005” (±1.3μm). For each position of the IMP (1-6), the six SMRs positioned in the measuring mesh are measured with seven points captured by SMR, being this procedure repeated for operator 1 and operator 2. The results obtained are included below and correspond to the biggest deviation in diameter with respect to the calibrated diameter value per position of the platform, the standard deviation per position and the standard deviation of all the measurements in the tests, see Table 8.

Table 8. Probing error of the size test results.

IMP position	Standard deviation (mm)	Maximum error (mm)
Position 1	0.0121	0.0205
Position 2	0.0096	0.0207
Position 3	0.0098	0.0230
Position 4	0.0436	0.0925
Position 5	0.0103	0.0208
Position 6	0.0102	0.0248
Maximum		0.0925
Mean		0.0337
Total	0.0198	

The average of the maximum diameter deviations, (d_i - d_{Cal}), among all the testing positions is 0.0337 mm and the maximum deviation 0.0925 mm, which corresponds to the position 4 of the platform. According to the results obtained in the rest of the platform’s positions, it seems to be observed a discrepancy in the values of position 4. The standard deviation of all the measurements in the test is 0.0198 mm, value which could be considered as reasonable for an AACMM. Furthermore, it is included in Fig. 6 the diameter deviation per SMR (1-6) and position of the platform (1-6). The values of deviation with regard to the calibrated diameter value are below 0.030 mm for all the SMRs and platform’s positions with the exception of the SMR 1 in the capture made for the position 4.

Fig. 6 Probing error of the size (diameter) test results per platform position (1-6) and SMR

The accuracy of an AACMM is inextricably linked to the skill of the operator and therefore to the contact force applied [42]. In [22] a contact force sensor for AACMM measurements is developed allowing this sensor the evaluation of the effect of contact force on AACMM performance. In order to show the influence of the skills of an operator in the accuracy of an AACMM measurement, the comparison of two operator’s measurements for the probing error of the size test could be seen in Fig. 7. According to the results obtained the operator 1 seems to be measuring with a higher repeatability among all the testing positions than operator 2, with the exception of the position 4 mentioned before.

Fig. 7 Probing error of the size test results, diameter deviation per operator

4.2. Volumetric performance test results

In the volumetric performance test it was performed a calculation of the distance error which shows the volumetric accuracy of the AACMM in most of its working volume. In this way, the distance between the centers of any of two SMRs measured with the laser tracker and AACMM is obtained, see Table 6. The distance error Di will be calculated as the difference of the distance between SMRs' centers measured with the arm L_i and the distance between the centers measured with the laser tracker L_{Cal}. The values obtained in the test are shown in Table 9 and correspond to the maximum distance deviation D_i, the range of distance deviations and 2RMS as twice the mean square root error of all the measurements.

Table 9. Volumetric performance test results

IMP position	2RMS (mm)	Mean Distance deviation (mm)	Max Distance deviation (mm)	Distance deviation range (mm)
Position 1	0.0670	0.0226	0.1043	0.1401
Position 2	0.0671	0.0243	0.0949	0.1284
Position 3	0.0603	0.0194	0.0903	0.1348
Position 4	0.1440	0.0615	0.1388	0.2139
Position 5	0.0879	0.0243	0.1541	0.1905
Position 6	0.0782	0.0280	0.1257	0.1859
Maximum			0.1541	0.2139
Mean		0.0300		
Total	0.0902			

As shown in the latter table, the 2RMS value obtained for all the measurements in the test is 0.0902 mm and the mean distance deviation 0.0300 mm. The maximum distance error corresponds to the position 4, as in the previous test, fact that leads us to conclude that there could be an error in the measurement in this position of the platform.

Fig. 8 describes the distance error of the AACMM calculated as a deviation with respect to the calibrated values measured with the laser tracker for each of the 15 distances between SMRs' centers evaluated and each test position of the platform (1-6). In most of the measurements, the distance errors obtained are below 0.040 mm with the exception of position 4. It is noteworthy that the distance deviation between the SMR3 and SMR4 presents the greatest value among all the distances evaluated. This could be due to the fact that both SMR are located in the ground, positions which are the most complex and forced for the AACMM measurement and therefore with the biggest probability of error during the measuring process.

Fig. 8 Distance error per platform position (1-6) and reference length

The values obtained in the performance tests described before using a laser tracker as reference instrument and the AACMM fixed on the IMP, are then compared with AACMM's verification results using the IMP and a conventional calibrated ball bar gauge. An example of the AACMM verification testing positions is shown in Fig. 9. Furthermore, the results are cross-checked with the AACMM maximum permissible error MPE provided by the manufacturer of the arm, see Table 10.

Fig. 9 Example of ball bar gauge test positions in verification procedure with indexed metrology platform.

Table 10. Volumetric performance test results: IMP with laser tracker as a reference (operator 1 / operator 2), IMP with ball bar gauge and manufacturer specification.

	IMP - LT Operator 1	IMP-LT Operator 2	IMP Ball bar gauge	AACMM Manufacturer data
Mean distance error (mm)	0.0300	0.0440	0.0203	
Max distance error (mm)	0.1541	0.1684	0.0902	
Distance error range (mm)	0.2139	0.2541	0.0899	
2RMS (mm)	0.0902	0.1217	0.0591	0.0430

The mean and maximum distance error calculated in the verification of the arm using the IMP and ball bar gauge are 0.0203 mm and 0.0902 mm respectively, meanwhile the values obtained in the verification tests with the laser tracker are 0.0300 mm and 0.1541 mm for the operator 1, and 0.0440 mm and 0.1684 mm for the operator 2. The 2RMS values in the tests with the laser tracker are 0.0902 mm and 0.1217 mm for operator 1 and 2, while in the evaluation with the IMP and the conventional gauge adopts a value of 0.0591 mm. The data provided by the manufacturer of the AACMM is 0.0430 mm.
In this work, it is also compared the results obtained in the AACMM verification using the laser tracker as a reference instrument, with the ones

obtained in an AACMM verification according to the standard ASME B89.4.22-2004 applicable to AACMM evaluation. An example of the AACMM verification volumetric performance test set up according to the ASME standard is shown in Fig. 10. Among all the tests included in this standard we will focus on the volumetric performance test with the following results included in Table 11.

Fig. 10. Example of test positions for AACMM ASME B89.4.22-2004 volumetric performance test.

Table 11. Volumetric performance test results with IMP with laser tracker as a reference (operator 1 / operator 2) and volumetric verification according to ASME B89.4.22-2004

	IMP - LT Operator 1	IMP - LT Operator 2	ASME B89.4.22-2004
Mean distance error (mm)	0.0300	0.0440	0.0298
Max distance error (mm)	0.1541	0.1684	0.0896
Distance error range (mm)	0.2139	0.2541	0.1456
2RMS (mm)	0.0902	0.1217	0.0766

In this case, the mean distance errors obtained with the laser tracker verification for the operator 1 and in the AACMM volumetric error evaluation according to ASME B89.4.22-2004 are very close, 0.0300 mm is the value obtained in the laser tracker test and 0.0298 mm in ASME evaluation. These results could lead us to confirm the suitability of the use of laser tracker equipment in verification procedures for AACMM.

5. Conclusions

After considering the results generated in the experimental testing carried out in this work, it could be concluded that the use of laser tracker equipment for AACMM calibration and verification procedures could be validated if the laser tracker's accuracy is guaranteed by means of its proper calibration or verification. It should be highlighted the fact that using a laser tracker as reference instrument in these procedures avoids the need of materializing the length required in a conventional gauge, increasing the flexibility for defining test positions and broadening the definition of reference lengths depending on equipment calibration or verification requirements. It is important to say that this procedure is dedicated for laboratories or institutions that could already have a laser tracker at their disposal, due to the high acquisition cost of this equipment in comparison with the use of a conventional one-dimensional gauge.

On the other hand, we would like to highlight that both accuracies of the AACMM to be calibrated and of the laser tracker should be taken into consideration so as to assure the feasibility of the procedure and the validity of the results obtained.

In this work, the values obtained in the performance tests using a laser tracker as reference instrument and the AACMM assembled on the IMP, were also compared with AACMM's verification results using the IMP and a conventional calibrated ball bar gauge, obtaining comparable mean and maximum distance errors with both verification procedures, fact that remarks the feasibility of the laser tracker usage as a reference instrument.

In addition and in order to include AACMM's verification requirements according to the existing standards, a comparison between ASME B89.4.22-2004 standard volumetric performance test results and the results obtained in the AACMM verification using the laser tracker as a reference instrument was carried out.

Finally it is worth mentioning that the usage of a laser tracker as a reference instrument together with the IMP with its mentioned advantages, allows to evaluate a larger working volume of the AACMM, reducing even more the time and man efforts required for AACMM calibration and verification procedures.

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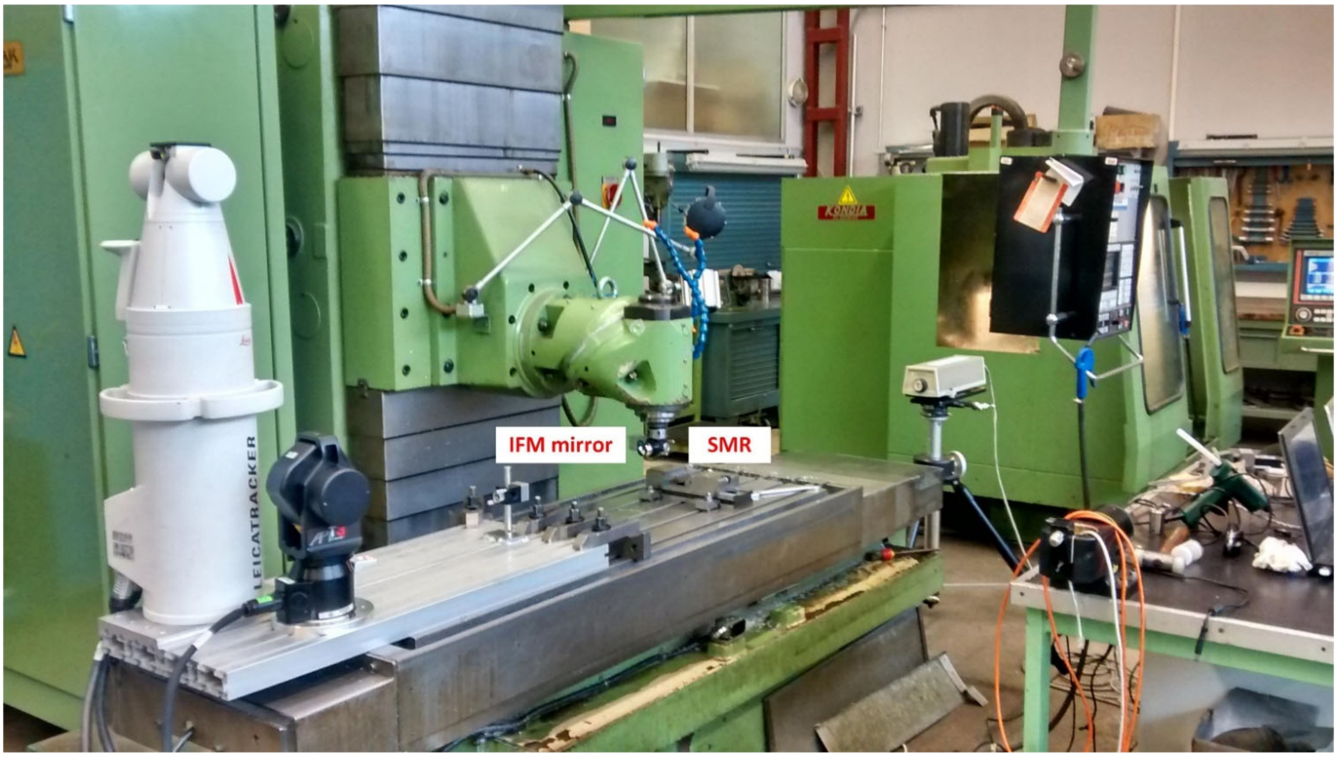

Fig. 1 Positioning of laser tracker and interferometer in the experimental test set up in machine tool

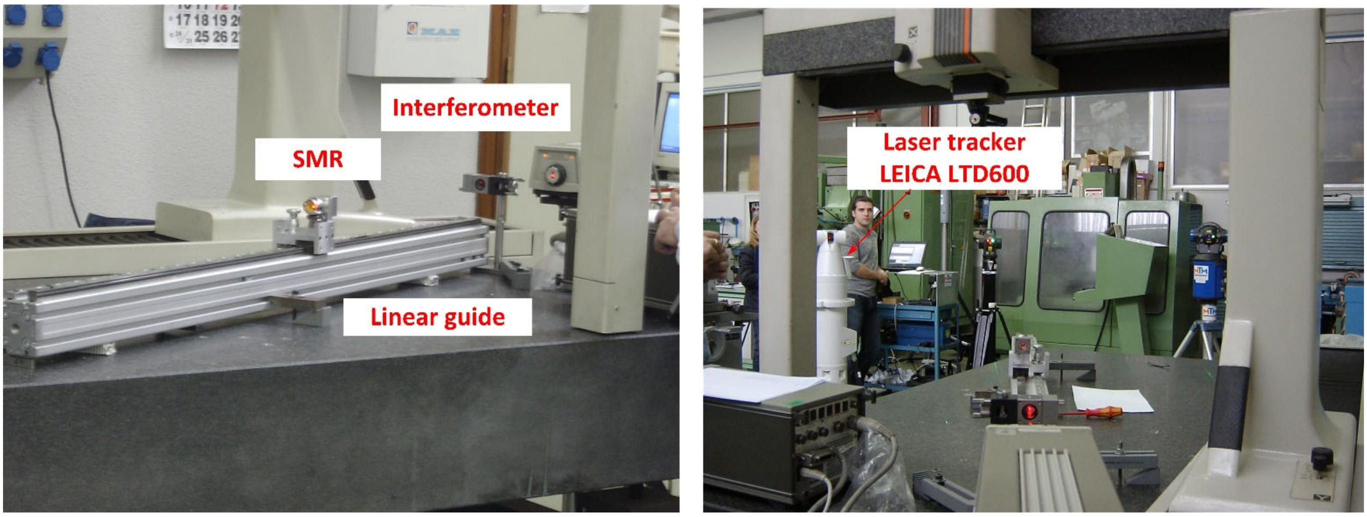

Fig. 2 Laser tracker and interferometer on linear guide experimental test set up

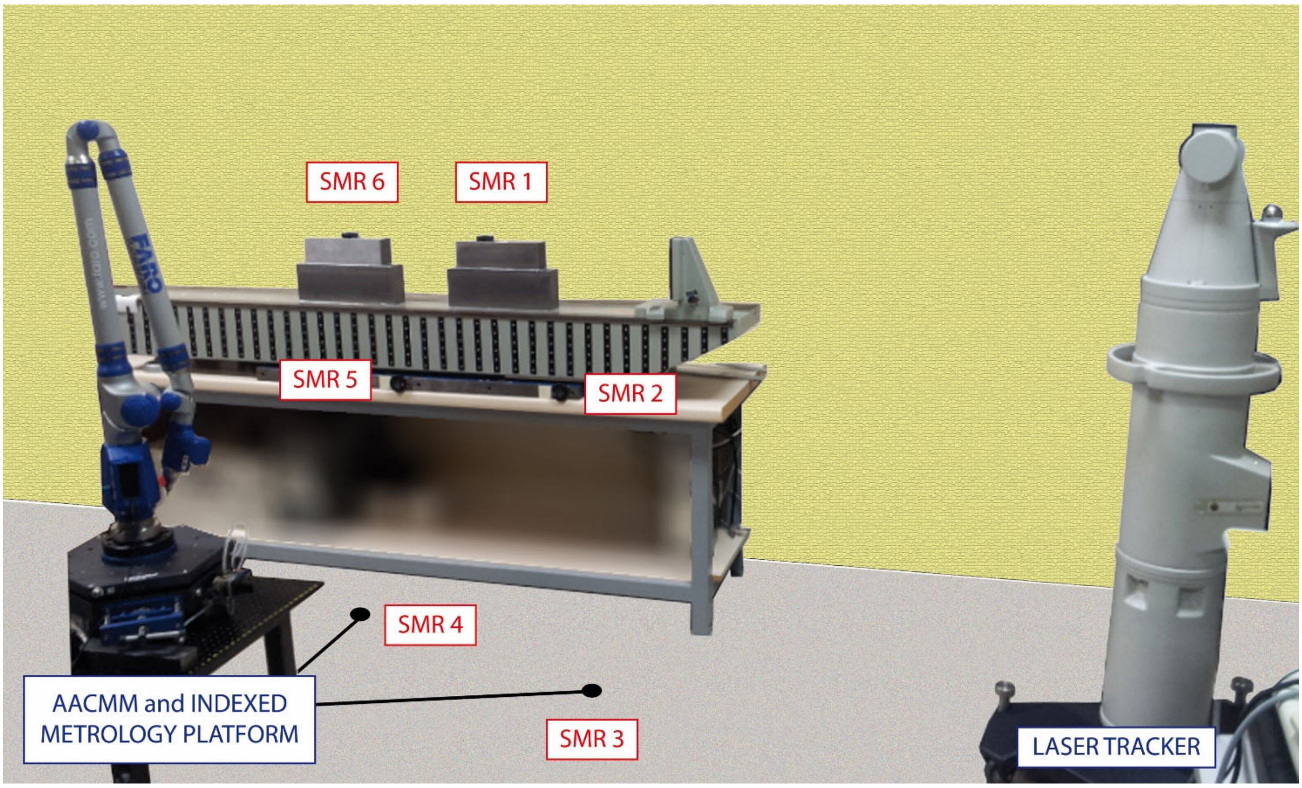

Fig. 3 Positioning of SMRs, AACMM and laser tracker in experimental test set up

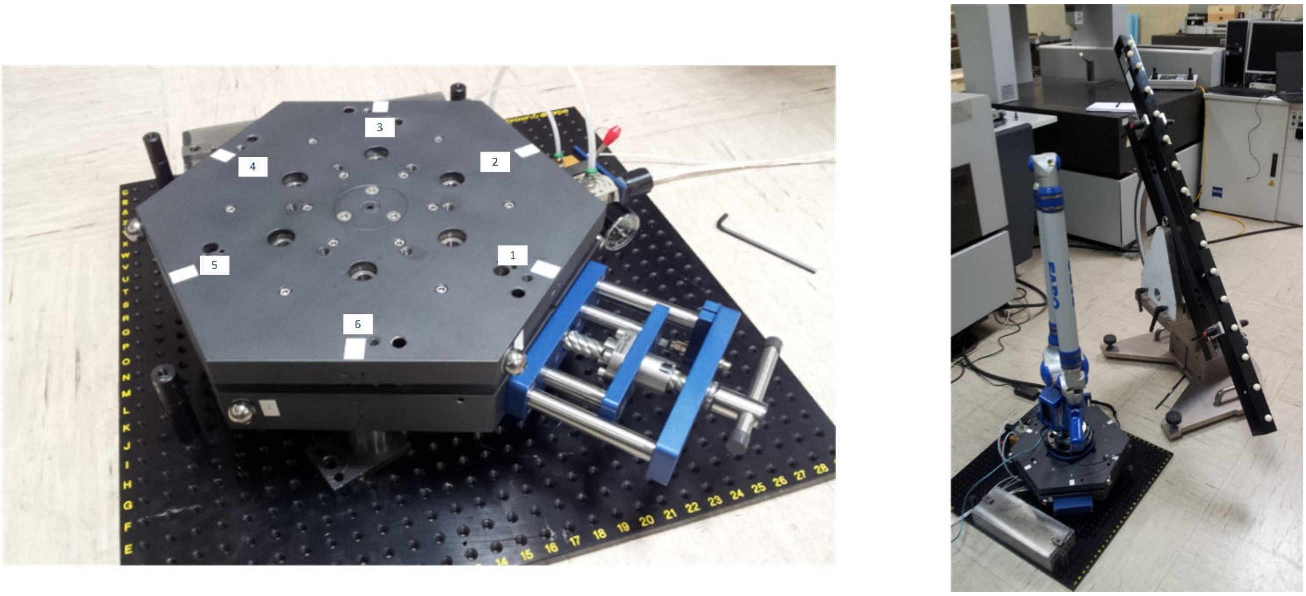

Fig. 4 Indexed metrology platform IMP rotating positions and example of test set up with IMP.

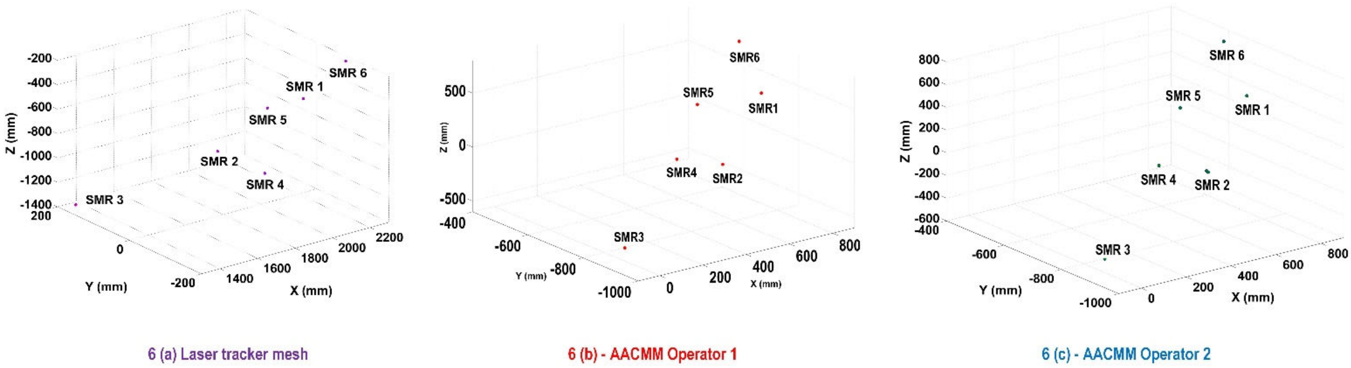

Fig. 5 SMRs positioning in the mesh according to laser tracker (5a) and AACMM measurement with Operator 1 (5b) / Operator 2 (5c) for IMP positions (1-6)

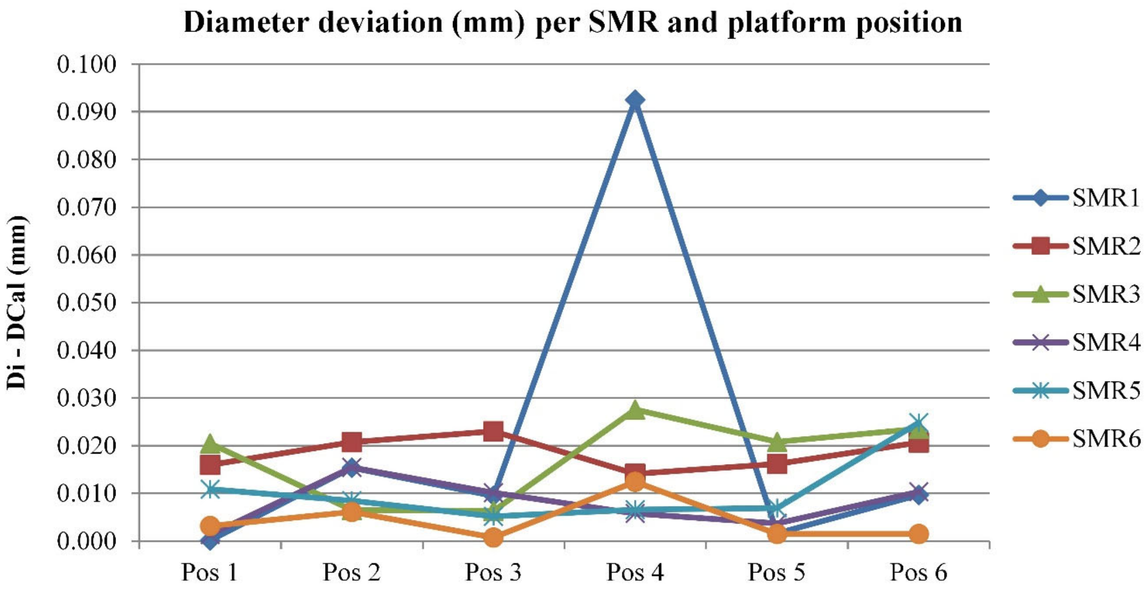

Fig. 6 Probing error of the size (diameter) test results per platform position (1-6) and SMR

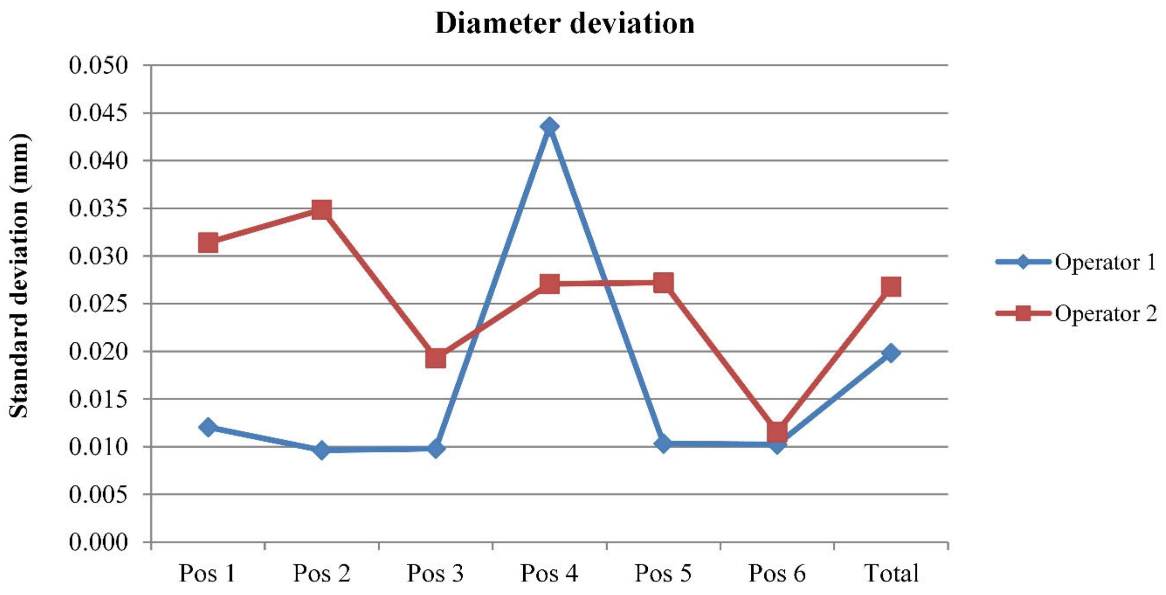

Fig. 7 Probing error of the size test results, diameter deviation per operator

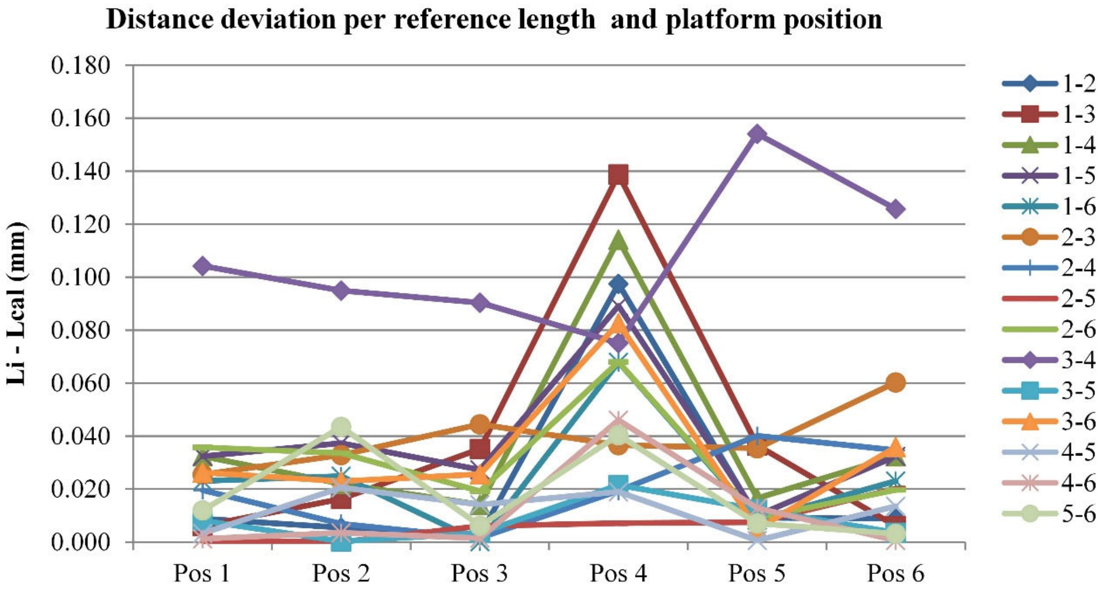

Fig. 8 Distance error per platform position (1-6) and reference length

Position1 Position2 Position3

Fig. 9 Example of ball bar gauge test positions in verification procedure with indexed metrology platform.

Position 1 Position 2 Position 3

Fig. 10. Example of test positions for AACMM ASME B89.4.22-2004 volumetric performance test.