Evaluation of a metrology platform for an articulated arm coordinate measuring machine verification under the ASME B89.4.22-2004 and VDI 2617_9-2009 standards.

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Abstract: *Portable coordinate measuring instruments such as articulated arm coordinate measuring machines (AACMMs) need to be periodically evaluated according to international standards and guidelines. This work presents a revision and comparison of the applicable standards for AACMMs evaluation together with a new proposal of using of an indexed metrology platform (IMP) as an alternative method to assess the volumetric accuracy of AACMMs. Two new verification procedures using the platform are explained including an innovative methodology based on the generation of virtual reference distances. The results of the IMP verification procedures, with and without virtual distances, were compared with the evaluation procedures according to the ASME B89.4.22-2004 standard and the VDI/VDE 2617-2009 part 9 guideline, in order to assess the suitability of the proposed verification procedures with the required traceability level. The main advantages of the use of the IMP are a reduction of testing time, labor and setups, facts that will generate consequently a simplification of the AACMM's verification techniques with the derived productivity increase.*

1. Introduction

Articulated arm coordinate measuring machines (AACMMs) are extensively used in the industry to inspect parts with complex geometry due to their flexibility, part surface accessibility and portable condition. The ASME B89.4.22-2004 standard [1], the VDI/VDE 2617-2009 part 9 guideline [2] and the draft of ISO/CD 10360 part 12 -2014 [3] are the internationally accepted documents that define and guide the verification processes for AACMMs with the required traceability level, enabling the metrological characterization of an AACMM in terms of its volumetric accuracy and repeatability. To perform the tests recommended in these standards, a calibrated gauge object must be located in different positions and orientations of the AACMM's working volume. The calibrated gauge object materializes the reference dimensions that are used to determine the AACMM's error in the measuring process.

The development of new gauges and techniques to perform verification and calibration procedures for AACMMs is ongoing, and related literature has been found. The use of calibrated reference objects for AACMM verification is inherited from its application to coordinate measuring machines (CMMs). There is a great variety of reference artifacts used in evaluation procedures of CMMs, for which verification procedures have been developed to calculate the 21 geometric errors of the machine and minimize the number of positions and orientations of the gauge [4], [5], [6] using one-dimensional, two-dimensional or three-dimensional artifacts. Gauge linear artifacts such as ball bars are the most common due to their easy to use concept, high accuracy and low cost in comparison to other artifacts. Standards [1] and [2] use this type of gauge in their specified testing protocols. Kovac and Frank [7] 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. [8]–[12] reported a method to calibrate an AACMM based on the Denavit-Hartenberg kinematic model parameters [13]. These parameters are optimized by measuring a calibrated ball bar gauge located at different orientations and positions of the AACMM's working volume. Sladek et al. [14] developed a metrological model to identify the kinematical parameters of a measuring arm as well as the errors associated with its measurements, and in references [15], [16] was established an online simulation system called a virtual articulated arm coordinate measuring machine, which evaluates the accuracy of the measurement and defines a compensation matrix using ball bar gauges. In [17], a new kinematic model of AACMMs based on a generalized geometric error model that eliminates the inadequacies of the D-H model was proposed. The calibration of the arm was performed using an Invar length gauge as reference artifact. An improved six parameter D–H model is established in [18] defying a set of new calibration and error compensation techniques for AACMMs with two parallel rotational axes. Regarding three-dimensional gauges, Shimojima et al. [19] presented a method to estimate the uncertainty of AACMMs, which involves the use of a three-dimensional ball plate gauge with nine balls oriented in five different positions. As a result, the kinematical parameters of each joint are determined. A similar approach for three-dimensional gauges is shown in [20]. Piratelli [21] introduced the development of virtual geometry gauges, virtual ball bars, to evaluate the performance of AACMMs. The proposed gauge has two groups, each with four holes, which are used to determine the points on the spherical surfaces. These points are fitted to spheres using computational algorithms, and the distances between the spheres' centers are calculated and compared to the calibrated length. In further works of the same author [22], [23], a virtual sphere plate gauge was developed by 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's extremity. Performance tests according to ASME B89.4.22, 2004 were performed, and the uncertainty of the virtual sphere plate was calculated. As mentioned in [21], the virtual sphere concept was applied in order to reduce the number of test positions specified in the standards [1]–[3] and to increase the efficiency of the verification procedure. Another approach to virtual spheres used for evaluation of AACMMs was described in [24] and [25], which presented a virtual circle gauge method that provides comparable information to the manufacturer's data. In this work, two gauges of anodized aluminum alloy with the shape of an inverted T profile and lengths of 1000 mm were manufactured, and three machined conical holes were used to determine the virtual circle. Gonzalez et al. [26], [27] analyzed 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, they proposed a probe's deflection model to reduce the diameter error. In [28] it was assessed the dynamic deformation of an AACMM developing a virtual simulation model to analyze the deformation influence in the measuring process. A similar approach was also presented by Vrhovec et al. [29], [30] with the aim of measuring the link deflection of the AACMM to minimize the elastic deformations as one of the main error sources affecting the measurement uncertainty. Introducing new features in a reference artifact, Cuesta et al. [31], [32] developed a new gauge with multiple physical geometries, including conical holes machined at the ends of the gauge to generate virtual spheres, for evaluation procedures of AACMMs. In [33], a method to identify the optimal geometric parameters of a measuring arm is described with the aim of determining its measurement uncertainty model. Additionally, the identification of the optimal measurement area for AACMMs, in order to improve the measurement's accuracy, has been addressed in [34]. Added to this, the same author proposes multiple measurement models to improve the measurement accuracy of AACMMs [35]. High range measuring instruments, such as laser trackers or laser tracers, have also been used in AACMM calibration procedures in [36] or [37], [38], in which Ostrowska presents a different approach to AACMM calibration using a laser tracer system as a standard of length and an industrial robot that replaces the operator and eliminates its influence in the measurement. They also show a comparison between the results of the new calibration procedure and the VDI 2617_9-2009 volumetric performance test. The same concept using a lacer tracer was also applied to CMM calibration procedures in former works of the authors [39], [40]. Monte Carlo simulation has been also used for developing AACMMs uncertainty models as in [41], [42] where Romdhani et al. developed a multi-level Monte Carlo simulation considering the main error sources that could affect the arm performance and the main variables influencing the measurand.

With regard to the tests specified in the standards for AACMM evaluation, ASME B89.4.22-2004 requires the implementation of the effective diameter, single point articulation and volumetric performance tests. Meanwhile, VDI/VDE 2617-2009 part 9 includes testing of probing error of the size, the form and the sphere location, complete with a testing of error indication for the size measurement. It should also be mentioned that the ISO/CD 10360 part 12 -2014 draft maintains the key aspects of ASME B89.4.22 and VDI/VDE 2617-2009 part 9 but includes some modifications to simplify the whole testing process. It comprises probing size and form, articulated location, and length error evaluation tests. However, these verification procedures are time consuming and expensive, and they generate an intense workload because the gauge needs to be relocated in several positions of the instrument's working volume during the testing.

For this reason, this work presents a new approach to verification procedures for AACMMs, including the use of an indexed metrology platform (IMP) as an auxiliary instrument. It also shows a qualitative and quantitative evaluation of the tests specified in the applicable standards [1]–[3] and finally compares the results obtained in the AACMM's verifications according to ASME B89.4.22 and VDI/VDE 2617-2009 part 9 with the results of the two new verification procedures developed for AACMMs using the IMP. In this way, the suitability of the indexed metrology platform for calibration and verification procedures of AACMMs can be assessed.

2. Guidelines and standards

As a starting point of the work, the above mentioned standards ASME B89.4.22-2004, VDI/VDE 2617-2009 part 9 and the existing draft of ISO/CD 10360 part 12 were analyzed to identify their main characteristics, similarities and differences with regard to the tests specified as can be seen in Table 1. We performed the performance tests for the AACMM according to the VDI and ASME standards. The volumetric verification procedure for AACMMs with the IMP was developed in this work by using the ASME B89.4.22-2004 standard as a reference.

Table 1. ASME, VDI, ISO standards testing summary for AACMM verification and calibration.

	VDI/VDE 2617-2009 part 9	ASME B89.4.22-2004	ISO/CD 10360 part 12 draft
1	Testing of probing error for the size	Effective diameter performance test	Probing size and form errors
2	Testing of probing error for the form		Probing size and form errors
3	Testing of probing error for the sphere location	Single point articulation performance test (SPAT)	Articulated location errors
4	Testing of error of indication for size measurement (entire or partial volumes)	Volumetric performance test	Length errors

2.1. Performance tests

The articulated arm coordinate measuring machine used in this work is a seven-axis Faro platinum arm with a diameter measuring 2.4 m and a 2-2-3 measuring configuration type. The manufacturer reported a volumetric accuracy of ±0.043 mm and single point repeatability of 0.030 mm. A ball bar gauge of 1400 mm was selected as a reference artifact to be used in the testing described in this paper.

2.1.1. Probing error of the size test

All the standards specify similar tests in order to evaluate the AACMM's accuracy in terms of size. According to ASME B89.4.22-2004, this test consists of measuring a calibrated sphere with a diameter between 10 and 50 mm located approximately in the middle of the reach of the arm. The largest deviation from the sphere calibrated value is reported as the maximum deviation.

The test specified in VDI/VDE 2617-2009 part 9 for the size evaluation includes a greater number of test repetitions and additional test positions for the calibrated reference sphere. These three test positions are distributed within three 120° sectors, and they are defined by the distance from the ball bar gauge to the AACMM (<30%, 30-70%, and >70% of the useful arm length) and the height (-20%, 0%, and 50% of the useful arm length). Five different orientations of the stylus must be considered. The probing error for the size (PS) is calculated as the maximum deviation from the three measured diameters to the calibrated value.

The ISO/CD 10360 part 12 draft defines similar test parameters with two testing positions and 25 measured points per sphere, which should be uniformly distributed. As stated in ASME B89.4.22-2004, the movement of the AACMM's articulations should be minimized. For each of the two test positions, the

Gaussian sphere diameter is calculated using the 25 captured points. The probing error for the size is calculated as the difference between the measured value and the calibrated one, which finally allows for comparison of this result with the maximum permissible error (MPE) given by the manufacturer.
The main parameters to be considered for the testing setup and evaluation according to the standards are listed in Table 2. The different heights of the ball bar gauge and the distances from the gauge to the AACMM considered for each test position are defined according to the standard's recommendations. It can be observed that in the case of VDI/VDE 2617-2009 part 9, the number of test positions and repetitions increases versus ASME B89.4.22-2004, a fact that may facilitate the evaluation of the AACMM's repeatability in a more accurate way. The experimental setups for both tests are shown in Fig. 1.

Table 2. ASME B89.4.22-2004, VDI/VDE 2617-2009 part 9 and ISO/CD 10360 part 12 tests to determine the size probing error.

	VDI/VDE 2617-2009 part 9	ASME B89.4.22-2004	ISO/CD 10360 part 12 draft
	Testing of probing error for the size	Effective diameter performance test	Probing size and form errors
Testing positions	3	1	2
Points / sphere	5	9	25
Repetitions	5	3	1
AACMM articulation	5 stylus orientations	Minimized for each measurement	Without changing stylus direction
Size	Sphere diameter (d =10 – 50mm)	Sphere diameter (d =10 – 50mm)	Sphere diameter (d < =51mm)
Error calculation	Probing error for the size, PS.	Largest diameter deviation to calibrated value	Probing size error, P_{Size}

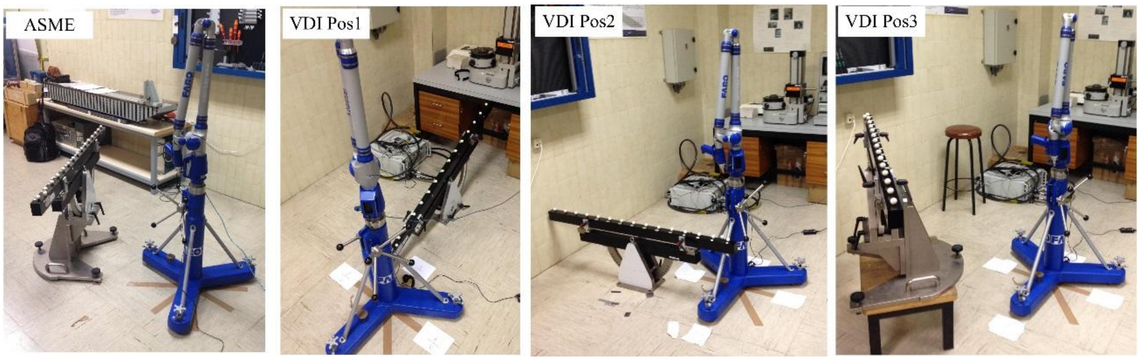

Fig. 1. Experimental setup of ASME B89.4.22-2004 and VDI/VDE 2617-2009 part 9 tests for probing error of the size.

2.1.2. Probing error of the sphere location test

An evaluation of the AACMM's ability to provide similar values of a point's coordinates at different AACMM poses was performed according to ASME B89.4.22-2004 with the single point articulation performance test (SPAT) and to VDI/VDE 2617-2009 part 9 with the probing error for the sphere location test. The main objective of this test is to determine the repeatability of the AACMM, taking into account different orientations of the AACMM with several arms' configurations for the same measured point. The VDI probing error for the sphere location (PL) was calculated by determining the coordinates of the center of a reference sphere at three different locations of the AACMM's working volume. The test setups according to the VDI standard are the same as that for the probing error of the size test shown in Fig.1. At each location, the sphere center's coordinates were determined by capturing five points per sphere, five repetitions with five different stylus orientations. For each testing position, the maximum distance between any two of the five centers was calculated, and the greatest value among the three testing positions was considered to be the probing error for the sphere location (PL).
The difference in the ASME single articulation performance test is the use of a kinematic seat instead of the reference sphere. This kinematic seat allows physical contact to be maintained with the probe,

reducing the influence of the AACMM's wrist orientation and arm position. To achieve the maximum number of orientations of the arm within the working volume, three test positions are defined. The first location shall be within a radius of up to 20% of the length of the arm, centered at the first rotational axis of the AACMM. The second location shall be within a zone between 20% and 80% of the length of the arm, and the third shall be outside a radius greater than 80% of the length of the arm. Ten different orientations of the AACMM are suggested to maximize the AACMM's articulation variation.

After ten repetitions, the following parameters are calculated: the maximum distance between the captured points, the average distance among the three testing positions (δmax), and $2\sigma_{SPAT}$ deviation. The setup for the ASME SPAT testing is presented in Fig. 2.

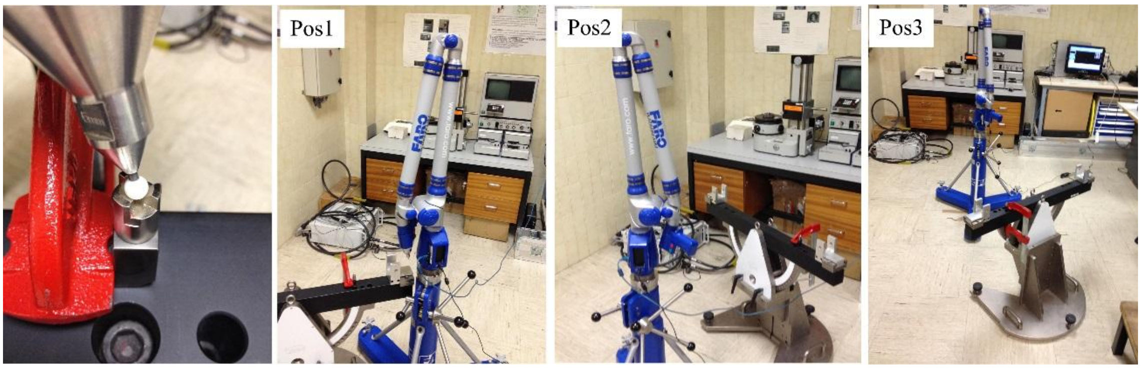

Fig. 2. Experimental setup of ASME B89.4.22-2004 SPAT.

The ISO/CD 10360 part 12 draft aims to probe the surface of a test sphere in a manner that extensively articulates the wrist by measuring with five orthogonal stylus orientations articulated at the wrist. It shows a similar test scheme to VDI/VDE 2617-2009 part 9 but reduces by one the number of test positions. The articulated location value (L_{Dia}), the minimum circumscribed sphere that encompasses the five sphere centers, is given as a test result, and it shall be compared with the specified manufacturer's value. Table 3 shows the comparison among the three standards for evaluating the ability of an AACMM to provide similar values of a point's coordinates at different AACMM poses.

Table 3. ASME B89.4.22-2004, VDI/VDE 2617-2009 part 9 and ISO/CD 10360 part 12 tests for probing error of the sphere location.

	VDI/VDE 2617-2009 part 9	ASME B89.4.22-2004	ISO/CD 10360 part 12 draft
	Testing of probing error for the sphere location	Single point articulation performance test, SPAT	Articulated location errors
Testing positions	3	3	2
Points / sphere	5	1	5
Repetitions	5	10	5
AACMM articulation	5 stylus orientations	5 arm positions/ wrist rotation 180º	5 stylus orientations
Location	Sphere center (d=10– 50mm)	Defined by a kinematic seat	Sphere center (d < =51mm)
Error calculation	Probing error for the sphere location, PL.	δmax, 2σ deviation.	Articulated location value, L_{Dia}

2.1.3. Volumetric performance test

The ASME and VDI volumetric performance tests were performed to evaluate the AACMM's accuracy in all its working volume. The test consists of measuring distances between spheres' centers, materialized on a calibrated ball bar gauge of 1400 mm length. The calibrated ball bar is located at different positions and orientations in the AACMM's working volume to establish whether the AACMM is capable of measuring within the maximum permissible error of length provided by the manufacturer.

In comparison with the probing error for the size and sphere location tests, the volumetric performance test could be considered more demanding and representative of the real working conditions of the

AACMM. Although the objective of this test is the same in all the standards, there are slight differences among their specifications, as shown in Table 4.

The highest number of positions is considered in ASME, and this increases the complexity of the procedure in terms of testing setup and time. VDI could be considered more demanding in terms of the repeatability evaluation of the AACMM due to the greater number of lengths materialized in the ball bar gauge and the repetitions defined per length. Finally, the ISO standard shows an intermediate step between ASME and VDI: it is equal to VDI in terms of repetitions and lengths, but it has a reduced number of test positions.

Table 4. ASME B89.4.22-2004, VDI/VDE 2617-2009 part 9 and ISO/CD 10360 part 12 tests for distance error evaluation.

	VDI/VDE 2617-2009 part 9	ASME B89.4.22-2004	ISO/CD 10360 part 12 draft
	Testing of error of indication for size measurement	Volumetric performance test	Length errors
Testing positions	12	20	7
Points / sphere	5	5	1
Repetitions	3 per length	1 per length	3 per length
Lengths / position	5	1	5
Position	Defined by sphere center	Defined by sphere center	Defined by sphere center
Error calculation	Error of indication for size measurement, E.	Max distance deviation, distance deviation range, 2RMS	Length measurement errors, E_{Uni}, E_{Bi}

Following the ASME B89.4.22-2004 recommendations, twenty testing positions are specified in our test, which considers these parameters: gauge length (short, 800 mm; and long, 1400 mm), ball bar gauge inclination (horizontal, vertical and 45°), ball bar gauge direction to the AACMM (radial or tangential for horizontal dispositions and 45°; see Fig. 3), ball bar gauge distance to the center of the working volume (near, within 600 mm from the center; and far, greater than 600 mm), ball bar gauge height (470 mm, 740 mm, and 1230 mm), and the octants affected.

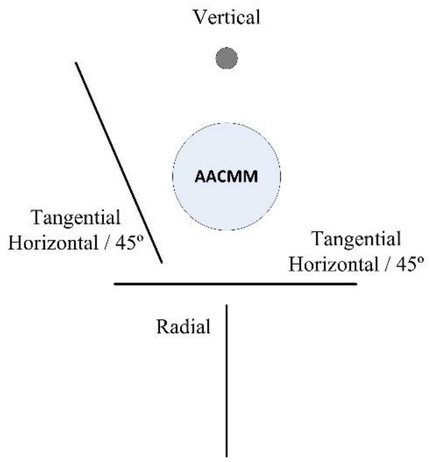

Fig. 3. Ball bar gauge direction scheme in volumetric performance test setup.

Since the purpose of the volumetric test is to evaluate the performance of the AACMM in its whole working volume, a division of eight approximately equal octants is accomplished by considering the AACMM's volume as a sphere whose center is located in the first encoder joint with a radius defined by the full length of the arm (see Fig. 4). This sphere is divided into upper and lower hemispheres by an equatorial plane parallel to the surface on which the AACMM is mounted. The equatorial plane is divided into four quadrants, which create eight equal volumes. Fig. 5 shows the experimental setup for four of the twenty testing positions defined as follows: two vertical, ten horizontal and eight with 45° inclination.

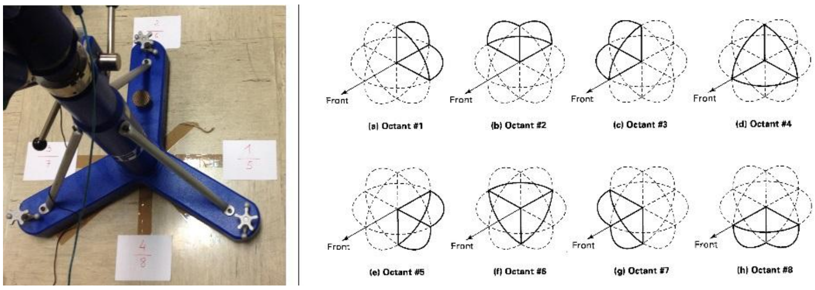

Fig. 4. Octants numbering scheme definition in volumetric performance test setup.

Position 1 Position 2 Position 3 Position 4

Fig. 5. Sample experimental setup positions for AACMM ASME B89.4.22-2004 volumetric performance test.

The center-to-center distance between the spheres was calculated by obtaining the distance error as the difference between the measured and the calibrated lengths. Three parameters are presented as final test results: the maximum deviation among test positions, the range of the deviations and the 2RMS value, determined as twice the root-mean-square of the deviations. These values are compared with the VDI volumetric testing results, the verification results of the AACMM using the IMP and the AACMM data provided by the manufacturer of the arm.

VDI/VDE 2617-2009 part 9 defines two possible tests that depend on the length of the reference artifact. Testing in partial volumes is permitted only in cases where the gauge is shorter than 66% of the body diagonal. In this case, the ball bar gauge used has a length of 1400 mm, and the diagonal distance of the measurement volume is 2400 mm. As a result, the working volume was divided into four partial volumes defined by the octant distribution shown in Fig. 4: volume 1 (octants 3/7-2/6), volume 2 (octants 2/6-1/5), volume 3 (octants1/5-4/8) and volume 4 (octants 4/8-3/7). For each partial volume, three measuring lines intersecting orthogonally for the ball bar gauge are settled, one radial to the AACMM and two tangential to the AACMM with 45° opposite inclination each, giving a total of twelve measuring lines in the whole working volume. Five test lengths are measured for each measuring line (200, 400, 600, 800 and 1000 mm), resulting in a total of sixty test lengths measured three times each. That gives a total number of 180 test lengths, exceeding the minimum number of 105 test lengths requested by the standard. The twelve measuring positions are listed in Table 5, and an example of the test setup is shown in Fig. 6.

Table 5. VDI/VDE 2617-2009 part 9 test positions summary.

Position	Partial volume ID	Ball bar gauge position	Test length (mm)
1	1	Radial	
2	1	Orthogonal 1 (ball bar inclination 45º)	
3	1	Orthogonal 2 (ball bar inclination 45º)	
4	2	Radial	
5	2	Orthogonal 1 (ball bar inclination 45º)	
6	2	Orthogonal 2 (ball bar inclination 45º)	200,400,600,800,1000
7	3	Radial	
8	3	Orthogonal 1 (ball bar inclination 45º)	
9	3	Orthogonal 2 (ball bar inclination 45º)	
10	4	Radial	
11	4	Orthogonal 1 (ball bar inclination 45º)	
12	4	Orthogonal 2 (ball bar inclination 45º)	

Position 1 Position 2 Position 3 Position 4

Fig. 6. Sample experimental setup positions for VDI/VDE 2617-2009 part 9 volumetric performance test.

For each individual measurement, the center-to-center distance of the spheres was calculated, and the distance errors were obtained as the difference between the measured and the calibrated lengths. VDI gives as a final result a representation of the individual errors per length, the error of indication for size measurements (E), which can be compared with the manufacturer's given value.

The ISO/CD 10360 part 12 draft defines five calibrated and well distributed test lengths to be measured along seven measurement lines. Each test length should be measured three times, considering the AACMM elbow's orientation. The test position is defined based on the measurement line (1-7), the ball bar direction (horizontal, vertical, or diagonal [45°]) and the azimuth angle. A minimum of 105 measurement lines is requested.

3. Verification procedure with an indexed metrology platform

This work presents the use of an indexed metrology platform as an auxiliary instrument in AACMM verification procedures, developing an alternative methodology to evaluate the volumetric accuracy and repeatability of the arm in comparison with the conventional procedures established in the standards [1–3]. Two different verification procedures using the indexed metrology platform will be compared with the verification procedures described in the standards. The first procedure uses solely the indexed metrology platform and a ball bar gauge located at different positions in the working volume of the arm. The second procedure is based on the generation of an unlimited number of virtual reference distances through the IMP's mathematical model [44], taking as a reference the measurements of a ball bar gauge located in a fixed testing position. The main advantage of the new procedures with the IMP is the reduction in the number of tests positions of the physical gauge required during verification. Alternatively to the procedures establish in the standards, the reduction in the testing positions is achieved by settling the calibrated gauge in a fixed position in the AACMM's working volume and measuring the gauge with the AACMM assembled on the IMP from the six platform rotating positions. In this way, when the platform rotates to a new position, which permits the AACMM to measure the same point in the ball bar gauge, a new working volume of the instrument is evaluated.

The indexed metrology platform is composed of two hexagonal platforms, one fixed lower platform and a mobile upper platform, which rotates every 60°, defining six different rotating positions. It has high mechanical repeatability, achieved through kinematic coupling configurations of spheres and cylinders. The orientation and position of the upper platform with respect to the lower platform is measured with six capacitive sensors, which have nanometer resolution, a measuring range of 100 µm for an output voltage from 10 to -10 V and an operational range from 100 to 200 µm. The sensors and targets are assembled in the upper and lower platforms where two coordinate reference systems are defined. Capturing the readings of the capacitive sensors each time we measure a point, we could generate a homogenous transformation matrix (HTM) that links the two coordinate reference systems through the mathematical model of the platform. Therefore, it is possible to express the coordinates of a point measured with the AACMM on the lower platform or global coordinate reference system.

To validate the use of the indexed metrology platform in the AACMM's verification procedure, it is necessary as a first step to estimate the indexed metrology platform's uncertainty. In this case, the uncertainty model of the platform was developed in a previous work of the authors [43], and it was assessed using the Monte Carlo simulation method. Table 6 shows the IMP's uncertainty values obtained from two distance measurements on a calibrated ball bar using the AACMM with the IMP. The values were obtained through a Monte Carlo simulation with 10000 iterations. The results validate the use of the IMP as an auxiliary instrument in verification procedures for AACMMs, considering the AACMM volumetric accuracy of ± 0.043 mm given by the manufacturer.

Table 6. Indexed metrology platform uncertainty in a distance measurement, n-iterations 10000

	d12 (Sphere 1 - 2)	d15 (Sphere 1 - 5)
Mean distance error (mm)	0.058721	0.063400
Standard deviation (mm)	0.000245	0.000242

3.1. Verification procedure of the AACMM with an indexed metrology platform

Following the integration of the kinematic models of the AACMM and the indexed metrology platform, the verification procedure to assess the volumetric performance of the arm with the IMP is explained.

Using a 1400 mm calibrated ball bar gauge, we performed a volumetric verification of the arm based on ASME B89.4.22-2004. The volumetric accuracy of the AACMM reported by the manufacturer is ± 0.043 mm. As explained in Table 4, the ASME volumetric performance test defines twenty different positions for the ball bar gauge to evaluate the AACMM's geometrical accuracy in all of its working volume. In this case, the AACMM is placed on the IMP, which allows the rotation of the AACMM into six different rotating positions, as seen in Fig. 7. Only five out of the twenty positions defined in the ASME standard are tested, but considering the six platforms' positions, the total number of achievable testing positions is thirty. Once the IMP rotates to a new position, allowing the AACMM to measure the same sphere, the values of the AACMM's angular encoders will be different, and a new working volume of the AACMM is evaluated on each IMP's position.

The AACMM rotates jointly with the upper platform during the verification procedure, enabling a big coverage of the AACMM's working volume and the definition of a broad number of testing positions but avoiding the movement of the calibrated gauge object during the verification. Thus, the number of the gauge testing positions is reduced and as a consequence the testing time and labor required in the procedure decrease, in comparison with the verification procedures described in the standards.

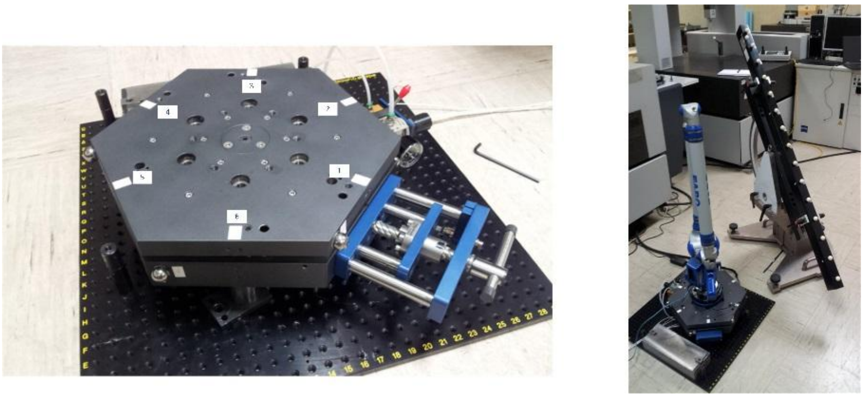

Fig. 7. Indexed Metrology Platform and example of test setup with IMP.

The ball bar gauge poses that are evaluated using the IMP are named as follows: 1- Vertical, 2- Horizontal, 3- Diag45Down, 4- Diag45Upward, and 5- Diag2Upward. For each of the five positions of the ball bar gauge and each position of the platform (1-6), we measured four or five spheres, depending on the position selected. Nine points per sphere were captured to determine the center of the spheres, calculating in this way the distance between spheres and the deviation in length versus the calibrated distance. The spheres measured for each position of the ball bar gauge during the verification procedure are shown in Fig. 8, Fig. 9 and Fig. 10.

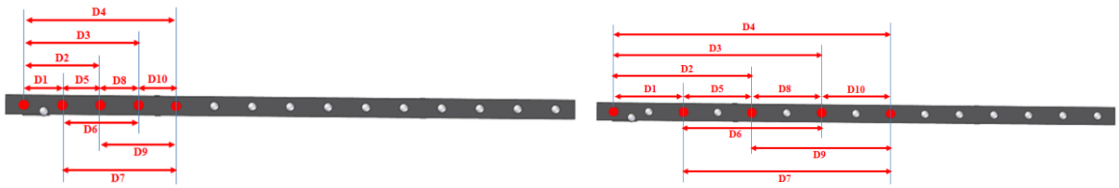

Fig. 8. Distance between sphere centers calculation (Position 1 and 2).

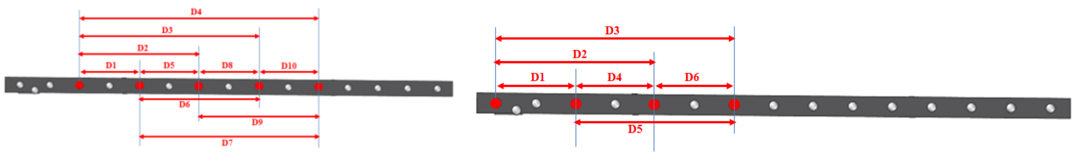

Fig. 9. Distance between sphere centers calculation (Position 3 and 4).

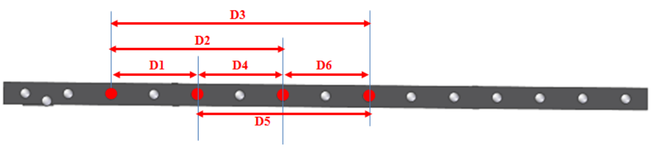

Fig. 10. Distance between sphere centers calculation (Position 5).

Considering the number of spheres measured in the five testing positions, we were able to materialize 252 distances between the centers in the six platforms' positions, comparing them to the nominal distances and obtaining 252 distance errors, which will be used to evaluate the volumetric performance of the arm.

3.2. Verification procedure of the AACMM with an indexed metrology platform and virtual distances

The second verification method for AACMMs using the platform included in this paper is the virtual distances methodology. In this procedure and as it was explained in section 3.1, the AACMM rotates jointly with the IMP into the six platforms' rotating positions. The virtual method enables the generation of an unlimited number of virtual reference distances through the IMP's mathematical model, based on the measurement from a selected platform's position of a physical reference artifact located in one specific position of the AACMM's working volume. The main advantages of the method are its flexibility for creating a wide number of distances and length dimensions and its requirement for only limited measurements of a physical gauge. This is extremely useful for high range measuring instruments, for which the reference distances to be evaluated have big dimensions, therefore requiring more complex testing of artifacts and space. This is the reason why the methodology was developed in a first step for high range measuring instruments such as laser trackers, as explained in [45]. It is important to remark, however, that the methodology could be applied to any portable coordinate measuring instrument, and the authors show in this paper the results of applying the virtual distances methodology to articulated arm coordinate measuring machines.

Because we can know with high accuracy the position and orientation of the upper or mobile platform with respect to the lower platform, it is possible to apply the rotation angle of the platform (60°) to generate virtual gauges rotated 60°, 120°, 180°, 240°, and 300° from the measured gauge in the selected position, which is taken as a reference. The measurements of the same gauge from the six positions of the platform will define the *measured points* in the method, resulting in six *measured gauges*. The Euclidean distances among the points measured will be named *measured distances*, one of the evaluation parameters of the volumetric performance test. In this case, we considered as a reference the gauge measured in the platform position number 1, and we name it *measured gauge 1*. The mathematical model of the IMP generates a homogeneous transformation matrix (HTM) that allows for a point captured with the AACMM assembled on the IMP to be expressed in the platform's global coordinate reference system located on the lower or fixed platform. Then, it is possible to generate a *virtual gauge 1* composed of several *virtual points* from the measurements of the gauge in platform position 1 through this mathematical model. By repeating this procedure successively for the six rotating positions of the platform, it would be possible to create six virtual gauges rotated 60° each, as shown in Fig. 11, where the disposition of the virtual gauges around the AACMM assembled on the indexed metrology platform can be seen. The position of the ball bar gauge, which was measured in the verification procedure with the AACMM from the six platforms' positions, was a 45° diagonal position tangential to the AACMM named Diag45Upward. This is also one of the gauge's positions measured with the AACMM and the IMP in the verification procedure explained in the section 3.1, and the details of the distance calculation can be seen in Fig. 9.

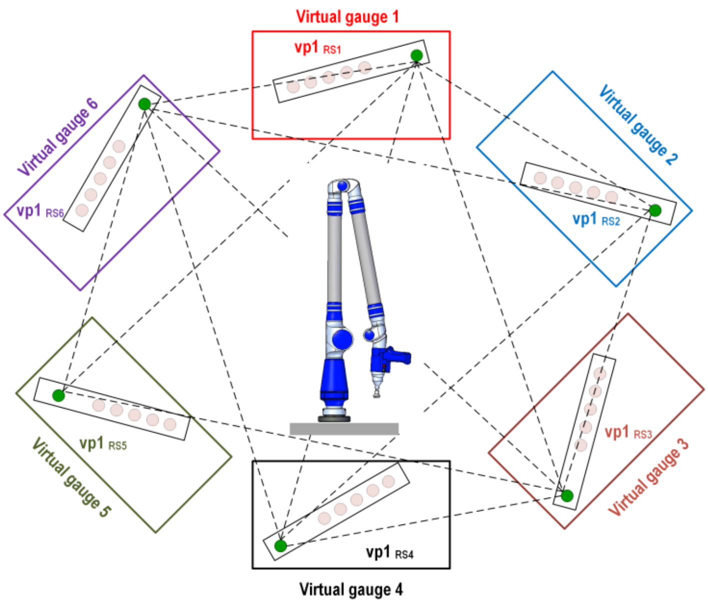

Fig. 11. Virtual gauges methodology's concept

4. Results

4.1. Probing error of the size test results

The results obtained in the ASME B89.4.22-2004 and VDI/VDE 2617-2009 part 9 tests are shown in Table 7. The largest deviation from the sphere calibrated value is reported as the maximum deviation. The standard measurement deviation is also calculated. The deviation in size is greater in the case of VDI testing, and this could be attributable to the different test positions of the gauge that were measured. In case of the ASME effective diameter performance test, the ball bar gauge remained fixed, and only repeatability was evaluated since three measurement repetitions were completed.

Table 7. ASME B89.4.22-2004, VDI/VDE 2617-2009 part 9 results for probing error of the size tests.

	VDI/VDE 2617-2009 part 9	ASME B89.4.22-2004	
	Probing error for the size	Effective diameter performance test	
Position 1 VDI (mm)	0.0598	-0.0082	Repetition 1 ASME (mm)
Position 2 VDI (mm)	0.0760	-0.0062	Repetition 2 ASME (mm)
Position 3 VDI (mm)	0.0247	-0.0103	Repetition 3 ASME (mm)
Max deviation / PS (mm)	0.0760	0.0103	
Standard deviation (mm)	0.0412	0.0021	

4.2. Probing error of the sphere location and single point articulation tests results

The comparative results among all the tests performed to determine the sphere location's error are listed in Table 8.

Table 8. ASME B89.4.22-2004 SPAT and VDI/VDE 2617-2009 part 9 results for probing error of the sphere location tests.

	ASME B89.4.22-2004			VDI/VDE 2617-2009 part 9
	Single point articulation performance test SPAT			Probing error for the sphere location
	2σ SPAT (mm)	δi range (mm)	Max distance / position (mm)	Max distance / position (mm)
Position 1	0.0622	0.0173	0.0391	0.0311
Position 2	0.0802	0.0389	0.0582	0.0639
Position 3	0.1219	0.0708	0.0856	0.1252
Maximum	0.1219	0.0708	0.0856	0.1252

By comparing in both tests the maximum values of the maximum distance error, it can be concluded that the value obtained in VDI testing (0.1252 mm) is higher than in ASME testing (0.0856 mm). In both tests, the biggest error value appears in position 3, where the ball bar gauge is located furthest from the AACMM, 1000 mm distance in case of VDI and 1200 mm in ASME. These results can be considered logical because in this position, the AACMM is working in its extreme measuring conditions, in which inherent arm errors and operator faults increase.

4.3. Volumetric performance test results

The final results of the volumetric performance tests according to the standards [1] and [2] are the maximum distance deviation among the tests positions, the range of distance deviations and the 2RMS value. These values were compared in Table 9 with the AACMM's verification results using the IMP with and without the virtual distances methodology explained in section 3 and with the data provided by the manufacturer of the arm, Faro.

Table 9. Comparison of IMP use, ASME B89.4.22-2004 and VDI/VDE 2617-2009 part 9 results for volumetric performance evaluation.

	ASME B89.4.22-2004	VDI/VDE 2617-2009	IMP	IMP Virtual distances	Faro
2RMS (mm)	0.0766	0.0383	0.0591	0.1185	0.0430
Mean distance deviation (mm)	0.0298	0.0152	0.0203	0.0507	
Max distance deviation (mm)	0.0896	0.0477	0.0902	0.1132	
Distance deviation range (mm)	0.1456	0.1009	0.0899	0.1072	

As noted in Table 9, the maximum distance error value obtained in the AACMM verification using the IMP (0.0902 mm), corresponding to position number six of the platform in a vertical ball bar gauge orientation, is very close to the value obtained in ASME B89.4.22-2004 (0.0896 mm). This result is reasonable because the testing positions defined in the arm's verification using the IMP took as a reference the ASME volumetric performance test positions. The use of the AACMM with the IMP allows for checking a bigger number of ball bar gauge orientations in comparison with the minimum number requested in the standards, and it therefore explores a larger probable working volume of the AACMM. This fact could explain why the maximum distance error values are higher in the testing with the IMP (0.0902 mm and 0.1132 mm) than in the procedures according to ASME (0.0896 mm) and VDI (0.0477 mm) standards. It should be noted that the 2RMS value obtained using the IMP without virtual distances (0.0591 mm) is lower than that obtained using the ASME standard (0.0766 mm) and bigger than that using the VDI standard (0.0383 mm) and the manufacturer value (0.0430 mm). The lowest range of the distance deviations appears in the verification using the IMP without virtual distances (0.0899 mm), as can be seen in Table 9.

If we compare the results obtained in the verification using the IMP with and without virtual distances, the errors in the virtual distances method are higher. It was assessed that the error increases with the length magnitude and that the virtual distances method enables testing of longer reference lengths that cover a range from 200 mm to 1700 mm. Meanwhile, in the verification method without virtual distances, the maximum reference lengths evaluated are 800 mm, and thus, the higher error values found with the virtual distances method are reasonable. The results obtained underline the proven position accuracy and repeatability of the IMP in the AACMM's verification procedure and its assessed suitability.

With regard to the results of the volumetric tests performed according to the standards VDI/VDE 2617-2009 part 9 and ASME B89.4.22-2004, Fig. 12 and Fig. 13 show the error obtained as distance deviation versus the calibrated value per test position. In the case of the VDI/VDE 2617-2009 part 9 evaluation (see Fig. 12), the distance deviations are shown for the measured reference lengths, which are represented on the horizontal axis of the graph. The reference lengths that are evaluated are 200, 400, 600, 800 and 1000 mm and the markers per test length show the results of the measurements of three gauge positions with three repetitions each. We could state here that there is no clear relation of the distance error with the reference length distances measured in all the positions. The distance error shows no linear behavior with the distance, concept that may apply to instruments with linear axes but not directly to AACMMs. These portable coordinate measuring instruments have a series of rotary joints that permit to express the coordinates of the point measured on the gauge by means of a nonlinear mathematical model which considers the rotation angle measured by the joint encoders and the arm's geometric parameters. Thus, the error will depend on the position and orientation of the joints during the measurement and on their combined influences through the kinematics of the arm.

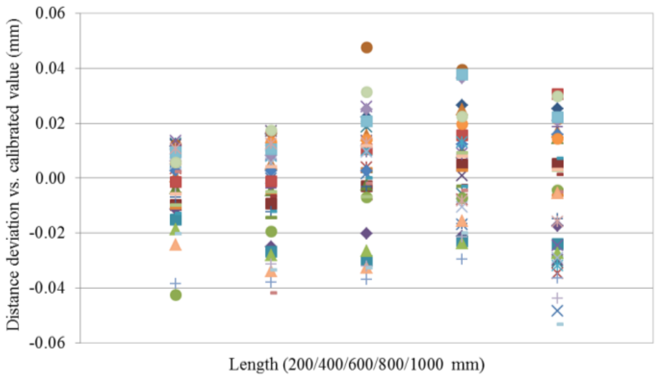

Fig. 12. VDI/VDE 2617-2009 part 9 distance error per reference length

In the ASME volumetric evaluation, see Fig. 13, the distance deviations are represented with the blue markers for the twenty test positions explained in section 2.1.3 which are represented on the horizontal axis of the figure. The red and green lines correspond to the maximum positive (0.08957 mm) and negative (-0.05608 mm) distance errors calculated as the deviation between the measured and calibrated length, obtaining a distance deviation range of 0.1456 mm. The maximum distance error value (0.0896 mm) is detected in the position 3 of the gauge that corresponds to a horizontal position of the ball bar situated at 1230 mm height with tangential disposition to the arm measuring a reference length of 800 mm. Position 18 shows the second higher distance error value (0.0783 mm) for a vertical position of the gauge, at 740 mm height with tangential disposition to the arm and a length of 1400 mm. Position 7 has the highest distance error with negative value (-0.0561 mm) versus de calibrated length and corresponds to a 800 mm reference length, diagonal position located at 1230 mm height.

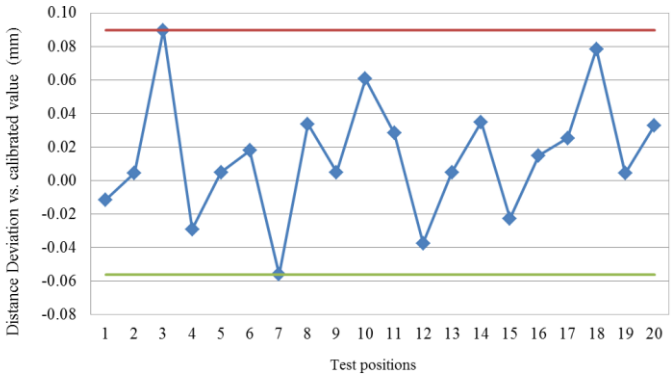

Fig. 13. ASME B89.4.22-2004 distance error per test position (1-20)

Finally, Fig. 14 and Fig. 15 show the distribution of the volumetric errors obtained in the tests performed according to the VDI and ASME standards. Both figures represent the ball bar gauge positions distributed in the AACMM's working volume, which is correctly covered as it could be seen in the figures, in a color scale depending on the error obtained in the measurement. Fig. 14 corresponds to the VDI volumetric performance results and shows shifted for each gauge position the five distances measured with the maximum error of the three repetitions per distance. As it could be clearly seen, the number of measurements in the VDI volumetric evaluation is higher than in the ASME evaluation. The AACMM working volume was divided into four partial volumes defined by the octant distribution and we represent them in Fig. 14 with the four red spheres intersecting themselves in the working volume.
The results of the ASME volumetric evaluation are shown in Fig. 15 being the gauge positions 3, 7 and 18 the ones with the highest distance error values as described previously in Fig. 13.

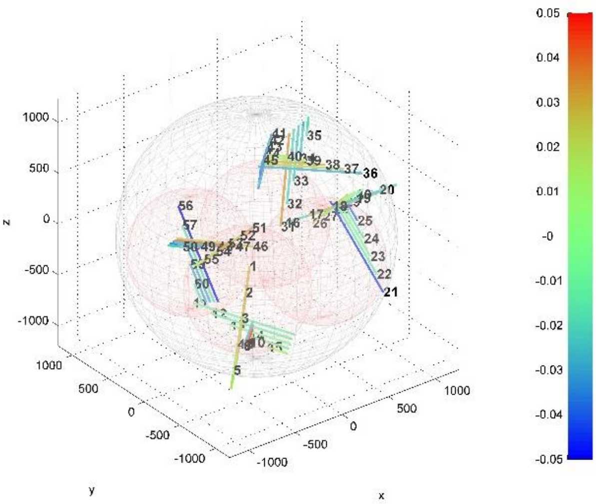

Fig. 14. Error map of VDI/VDE 2617-2009 part 9 volumetric performance test.

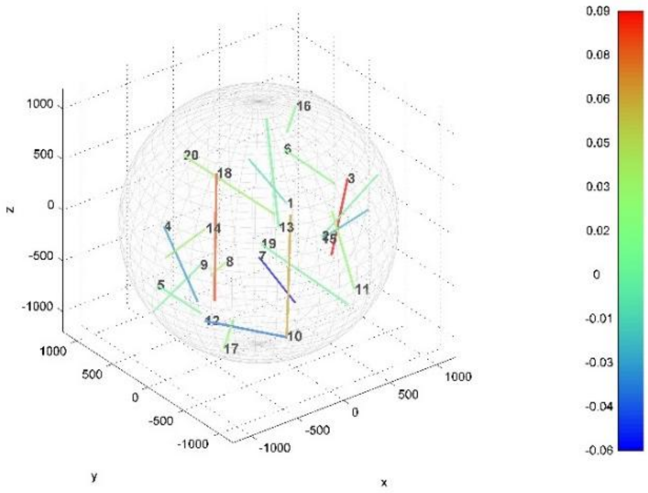

Fig. 15. Error map of ASME B89.4.22-2004 volumetric performance test.

5. Productivity analysis of the indexed metrology platform in AACMM verification procedures

Productivity can be defined as a measure of the efficiency of a person, machine or system in converting inputs into useful outputs [46]. It is computed by dividing the average output per period by the total costs incurred or resources consumed in that period. In this work, the verification procedure for an AACMM is computed in terms of working hours per operator who will be performing the verification and calibration tests. A big advantage of the new AACMM verification procedures with the IMP presented in this paper is the huge reduction of the time invested in the verification itself and the minimization of the man effort derived from the use of the platform. As explained before, the calibrated gauge object remains in a fixed position during the verification, and the measuring instrument placed on the IMP rotates with respect to the calibrated gauge object during the verification procedure. This is a significant improvement due to the reduction in the number of the gauge's testing positions and the time for defining and implementing the different test positions. In comparison with the ASME standard, the reduction of physical test positions with the new verification procedures is 75%, making it necessary to define only five testing positions for the ball bar gauge versus the twenty defined in ASME. The testing time of the AACMM verification process using the IMP is approximately 3.5 hours versus the 12.6 hours invested in the ASME volumetric performance test or the 12.5 hours in case of VDI, showing that these results are a clear improvement compared to the conventional procedures defined in the standards.

Table 10 shows an evaluation of the time invested in the verification procedures according to ASME and VDI standards and the IMP method, including the concepts of setup time and measuring time. As well, a cost estimation is provided, which considers an average cost of 60 euros per hour. With regard to time and manpower, we can conclude that most of the time is invested on the test setup in the case of ASME. Volumetric performance tests are the most time consuming due mainly to the great number of gauge positions and reference distances to be measured. VDI emphasizes the number of repetitions per test, which is related to repeatability evaluation, while ASME increases the number of test positions, fact that is proved with the higher setup times measured in the ASME testing. A detailed description of the number of test measurements is shown in Table 11, being the number of test measurements performed higher in VDI than in ASME.

Table 10. Evaluation of ASME B89.4.22-2004, VDI/VDE 2617-2009 part 9, IMP testing time and cost.

	ASME B89.4.22-2004				
	Set up time (min)	Measuring time (min)	Total time (min)	Total time (hrs.)	Cost (EUR)
Effective diameter test	150	10	160	2.67	
SPAT	60	40	100	1.67	
Volumetric performance test	660	100	760	12.67	
TOTAL	870	150	1020	17	1020
	VDI/VDE 2617-2009 part 9				
Size and sphere location test	90	60	150	2.5	
Volumetric performance test (partial volumes)	390	360	750	12.5	
TOTAL	480	420	900	15	900
	Indexed Metrology Platform (IMP)				
TOTAL	80	130	210	3.5	210

Table 11. Evaluation of ASME B89.4.22-2004 and VDI/VDE 2617-2009 part 9 number of measurements per test type.

	ASME B89.4.22-2004				
	Gauge positions	Lengths	Spheres	Repetitions	Measurements
Effective diameter test	1		1	3	3
SPAT	3			10	30
Volumetric performance test	20	1	2	1	40
	VDI/VDE 2617-2009 part 9				
Probing error for the size and sphere location	3		1	5	15
Error of indication for size measurement (partial volumes)	12	5	2	3	360

6. Conclusions

This work presented the analysis and evaluation of the use of an indexed metrology platform (IMP) as an alternative method to evaluate the volumetric accuracy and repeatability of an AACMM, comparing the obtained results with those according to the ASME B89.4.22-2004 standard and the VDI/VDE 2617-2009 part 9 guideline. In addition, the new ISO/CD 10360 part 12 -2014 draft was included in the analysis to extend the comparison range.

Two new procedures for AACMMs verification using the platform, with and without virtual distances, were presented, evaluated and compared with the results of the evaluation tests according to the standards ASME B89.4.22-2004 and VDI/VDE 2617-2009 part 9 guideline. The first procedure uses solely the indexed metrology platform and a ball bar gauge located at different positions in the working volume of the arm. The second procedure is based on the generation of an unlimited number of virtual reference distances through the IMP's mathematical model, taking as a reference the measurements of a ball bar gauge located in a fixed testing position. The main advantage of the new procedures with the IMP is the reduction in the number of tests positions required of the physical gauge during verification settling the calibrated gauge in a fixed position in the AACMM's working volume and measuring the gauge with the AACMM assembled on the IMP from the six platform rotating positions. In this way, when the platform rotates to a new position, which permits the AACMM to measure the same point in the ball bar gauge, a new working volume of the instrument is evaluated. The definition of five physical testing positions for the ball bar gauge complemented with the six rotating positions of the platform enables a complete and accurate evaluation of the AACMM's working volume, as it is assessed in this work. The simplification of the testing setup is one of the major benefits of the new procedures considering the testing facilities and reference instruments required. Testing time is reduced up to 75%. The total time of the AACMM verification process using the IMP is approximately 210 minutes (3.5 hours) corresponding 80 minutes to setup time and the remainder 130 minutes to measuring time. The comparison with the 12.6 hours invested in the ASME volumetric performance test or the 12.5 hours in case of VDI, showed that the IMP results are a clear improvement compared to the conventional procedures defined in the standards. This would be highly appreciated by laboratories or the industrial sector, where calibration and verification procedures for AACMMs are periodically performed.

Concerning the test results, the maximum distance error values obtained in the AACMM's verification tests using the IMP with and without the virtual distances methodology (0.0902 mm and 0.1132 mm) compared with those obtained in the volumetric performance tests according to the standards, ASME (0.0896 mm) and VDI (0.0477 mm), underline the proven position accuracy and repeatability of the IMP in the AACMM's verification procedure. It is important to highlight that the results obtained with the IMP (0.0902 mm) are very close to those generated in the ASME B89.4.22-2004 evaluation (0.0896 mm) because the five testing positions defined for the AACMM verification with the IMP took as reference the ASME volumetric performance test positions. The joint use of the AACMM with the IMP allowed for testing a larger number of ball bar gauge orientations in comparison with the minimum number requested in the standards. Therefore, a probable larger working volume of the AACMM was explored. This fact could explain the higher maximum distance error values obtained for the IMP testing, which equally reaffirms the suitability of the 2RMS value obtained (0.0591 mm).

According to the results generated in this paper, it can be concluded that the indexed metrology platform is an adequate device to be used in AACMMs calibration and verification procedures by accounting for the required accuracy of the measuring instrument. The results showed a significant improvement in terms of testing setup and testing time reduction.

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