DOI 10.1007/s00170-015-7648-3

Verification of a laser tracker with an indexed metrology platform

R. Acero[1*], J. Santolaria[2], M. Pueo[1], A. Brau[3]

1 Centro Universitario de la Defensa. Academia General Militar. Crta. Huesca s/n. 50090, Zaragoza, Spain
2 Department of Design and Manufacturing Engineering, University of Zaragoza. María de Luna 3, 50018 Zaragoza, Spain
3 Department of Industrial Engineering, University of Sonora, Rosales y Blvd. Luis Encinas S/N, C.P. 83000, Hermosillo, Sonora, México
* Corresponding author. Tel. +34 976739831, fax +34 976739824, E-mail: racero@unizar.es

KEYWORDS: laser tracker, indexed metrology platform, mesh, verification

This work presents the development of a new verification procedure for laser trackers with an indexed metrology platform. The applicable standards which guide the calibration and verification procedures for laser trackers are ASME B89.4.19 - 2006, VDI/VDE 2617- 2011 part 10 and the draft of ISO/CD10360-10 standard. All of them define a range of comparable tests for evaluating the performance of a laser tracker using calibrated artifacts for reference lengths definition. In this case, the use of an indexed metrology platform enables the evaluation of different working volumes of the laser tracker using the same physical calibrated gauge which remains still during the verification procedure meanwhile the laser tracker rotates with the platform. This is possible due to the six rotating positions of the platform and its ability to express points in a global reference system located in the lower platform. To overcome this, the kinematic modeling of the laser tracker is made together with its integration with the mathematical model of the platform. Then, the theoretical verification procedure of the laser tracker with the indexed metrology platform is developed, followed by an experimental phase where the verification procedure is carried out with a big dimension mesh of retroreflectors and a physical gauge which is used as a reference. The results obtained in the verification procedure validate the use of the indexed metrology platform in verification procedures for laser trackers, showing its advantages in terms of coverage of the instrument working volume, testing time reduction and test set up simplification.

1. Introduction

Portable coordinate measuring instruments are extremely flexible equipment for complex measurements due to their portable condition but many times they are used in changing environmental conditions. For this reason, in order to assure the reliability of the measurements, periodical calibration and verficiation procedures need to be carried out with these instruments. The first developments of measurements based on laser trackers date back to the 1980's to estimate and calibrate robots accuracy and positioning errors respectively [1]–[4] . But dimensional verification of big dimension parts mainly in aeronautic and aerospace industries, fostered [5] the usage of high range measuring instruments based on laser technology such as laser trackers and laser scanners, that are also used for machine tool calibration and verification [6] or deformation analysis [7]. The laser tracker is a portable measurement device that measures the spherical coordinates of a moving reflector by means of a laser beam. The distance to the reflector is measured with interferometer (IFM) or absolute distance meter (ADM) and two optical angle encoders measure the direction to the reflector. Its working principle [8], [9] is based on a laser beam emitted by the interferometer which is divided into two by a beam splitter. The reflector returns the laser beam back to the laser tracker but in case the reflector moves, the relative movement could be quantified with part of the laser beam that is directed to a position sensor device (PSD). The PSD measures the reflected beam offset and generates an output signal to the control unit which will assure the centering of the laser beam back to the reflector.

Verification and calibration procedures of laser trackers are tedious and time intensive tasks and are based on the current ASME B89.4.19 - 2006 [10] and the draft of ISO 10360-10 [12] standards and the technical recommendation VDI/VDE 2617- 2011 part 10 [11]. These standards define a range of evaluation tests where laser tracker measurements of points from calibrated gauges are carried out. These gauges could be calibrated gage blocks, step gauges, ball bars or other gauge types with spherical or parallel geometries with an associated uncertainty lower than the maximum permissible error given by the laser tracker manufacturer. Due to the great calibrated dimensions needed in the verification procedures for high range measuring instruments, the concept of reference length defined by two points is used in this work. The reference points can be defined by for example the centers of retroreflectors located on fixed structures creating the concept of a retroreflectors' mesh that must be previously calibrated. The measurements on the reference lengths could be made with interferometer (IFM) or absolute distance measurement (ADM) placing the calibrated reference length in several positions and orientations of the instrument's working volume. It is important to point out the sensitivity of the tests described in the standards to different geometric misalignments in the diverse laser tracker designs. This fact has been discussed in [13] and in [14] analizing the tests included in the standards [10], [11] and [12]. Additional literature in regard to verification and calibration procedures developed for laser trackers has been found. In [15] it is proposed a laser tracker calibration procedure to determine the alignment and angle encoder errors of a laser tracker together with their uncertainties by means of a set of fixed targets. An approach to a new simple method to estimate scale errors in the horizontal angle encoder of laser tracker with a non calibrated but stable length is presented in the work of [16]. Gassner and Ruland [17] developed a laser tracker horizontal angle calibration test stand based on a high precision rotary table. Nasr et al. [18] compared and described in their work different methodologies for calibrating the laser tracker's angle encoder errors such as the National Institute of Standandards and Technology (NIST) technique [16] , the NPL [15] and a precision angular indexing table technique. The authors in [19] examined different techniques that required the laser tracker's probing system to be in continuous movement during the testing. In this case, physical geometries were used representing a plane, circle and line where a spherically mounted retroreflector (SMR) moves.

In order to optimize these calibration and verification procedures for laser trackers, in this work the use of an indexed metrology platform (IMP) to develop an alternative methodology to evaluate the volumetric accuracy and repeatability of a laser tracker is analyzed and compared to the conventional procedures established in the standards [10], [11], [12] which were used as a basis for the development of this novel verification procedure. The indexed metrology platform is composed of two hexagonal platforms [20], one fixed lower platform and a mobile upper platform which rotates around the fixed one every 60º, defining six different rotation positions as could be seen in Fig. 1. The mechanical repeatability of the platform is 0.7 μm, which is achieved by means of kinematic couplings configuration of spheres and cylinders. Three reference spheres are located on each platform to allow the determination of the reference systems of both platforms in order to express the coordinates of a captured point by the laser tracker in the fixed lower platform or global coordinate reference system during the verification procedure. The indexed metrology platform presents a high mechanical position repeatability that allows to measure with high precision the position and orientation of the upper platform with respect to the lower platform [21]. This feature is accomplished with the use of six capacitive sensors with nanometer resolution with a measuring range of 100 μm for an output voltage from 10 to -10 V and an operational range from 100 to 200 μm. Their sensors and targets are assembled in the upper and lower platforms respectively. The coordinates of the points measured with the laser tracker in the verification procedure are obtained in a fixed global coordinate reference system located in the lower platform by means of a mathematical model explained in [21], where a homogenous transformation matrix (HTM) is found allowing the change of coordinate reference systems required. The integration of the laser tracker kinematic model and the mathematical model of the platform enables to express a point captured by the laser tracker in the global platform coordinate reference system. The kinematic model of the laser tracker developed in this work is based on the Denavit Hartenberg algorithm (D-H) [22] . This model has been broadly applied to robots and articulated arm coordinate measuring machines (AACMMs) starting with the Hayati-Mirmirani [23] approach in 1985 where a new robot calibration method is developed including any combination of revolute and prismatic joints by means of a new rotation parameter β_i that links consecutive frames with parallel axis. Models with five parameters were also proposed by Hayati [24] for prismatic joints. Hsu and Everett [25], [26]–[28] and [29] developed models with five parameters including any joint type. The D-H model has been also used for laser tracker kinematic modelling as a previous step for parameter identification in calibration procedures [30].

The ability to express points in a global coordinate reference system is one of the main features and advantages of the indexed metrology platform because it allows to reduce the test positions of the reference gauge, which is the retrorreflector mesh in this case, in comparison with the positions defined in the current standards [10], [11], and [12] which are compensated with the six rotating positions of the platform. This is a remarkable benefit for high range measuring instruments' calibration and verification procedures due to the big reference lengths needed to be materialized in the reference artifact [31]. In this way, each time the platform rotates to a new position the laser tracker measures the same retroreflector with different values of the laser tracker angular encoders, and thus a new working volume of the instrument is evaluated. The use of the laser tracker with the indexed metrology platform simultaneously, enables a greater and satisfactory exploration of the laser tracker working volume as it is described in this paper. In the verification procedure developed, it is the measuring mesh itself the one that it is used as a reference artifact, being able to characterize the error by the reproducibility or fixed point tests carried out independently of the laser tracker's error source. This is possible because of the use of the indexed metrology platform as an auxiliary instrument in the verification procedure developed for the laser tracker. The indexed metrology platform allows us to know with high accuracy the position from the upper platform where the laser tracker is fixed, with respect to the fixed lower platform where the global coordinate reference system is located. In this work a new verification procedure for laser trackers with a capacitive sensor based indexed metrology platform is presented.

Fig. 1 Indexed metrology platform

2. Kinematic model integration.

In order to be able to use the laser tracker together with the indexed metrology platform it is necessary to integrate the kinematic model of the laser tracker and the mathematical model of the platform. This integration determines the mathematical relation between them and will allow us to express the coordinates of a point measured with the laser tracker in the global reference system of the indexed metrology platform. In this work, the kinematic modelling based on Denavit Hartenberg model (D-H) [22] of a laser tracker model API-T3-15 m with laser source in the rotating head was carried out. The laser tracker has two rotatory and one linear joint [32]. The angular encoders for the horizontal and vertical rotation will give the angle rotation values for the rotatory joints and the distance value will be measured with the interferometer. Using the D-H model, the coordinates of a point measured with the laser tracker in terms of the angles and distance values of the kinematic chain could be obtained. The kinematic model according to D-H model is shown in Fig. 2 including a global coordinate reference system (x_0, y_0, z_0), one reference system on each rotatory joint and the third coordinate reference system located in the retroreflector (x_3, y_3, z_3).

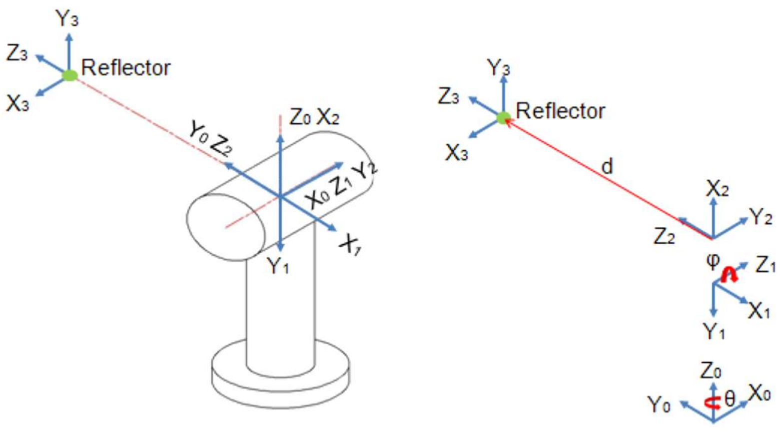


Fig. 2 Coordinate reference systems in laser tracker API T3 model according to D-H model

The initial values of the geometric parameters of the D-H model di, ai, θi and αi are included in the Table 1 with *θ, φ* and *d* as articulation variables.

Table 1. D-H model geometric parameters initial values

Joint	θi (º)	αi (º)	ai (mm)	di (mm)
1	θ - 90º	-90	0	0
2	*φ* - 90	90	0	0
3	-90	0	0	d

The notation to express a point measured with the laser in a global coordinate reference system with origin in the laser tracker (x_0, y_0, z_0) initially expressed in the retroreflector reference system (x3, y3, z3), in terms of *θ*, *φ* and *d* will be defined by the equation (1).

$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}_{x0,y0,z0\ (SR0)} = {}^{0}T_{3} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}_{X3,Y3,Z3\ (SR3)} \quad (1)$$

Denoting ${}^{0}T_{3}$ as the homogeneous transformation matrix (HTM) expressed in terms of the product of successive coordinates transformation matrixes ${}^{i-1}A_i$ where *θ* and *φ* are the values obtained from the angular encoders and *d* the distance measured with the interferometer as included in equations (2), (3), (4) and (5):

$${}^{0}T_{3} = {}^{0}A_{1}\,{}^{1}A_{2}\,{}^{2}A_{3} \quad (2)$$

$${}^{0}A_{1} = \begin{bmatrix} \cos(\theta-90) & 0 & -\sin(\theta-90) & 0 \\ \sin(\theta-90) & 0 & \cos(\theta-90) & 0 \\ 0 & -1 & 0 & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$ {}^{1}A_{2} = \begin{bmatrix} \cos(\varphi-90) & 0 & \sin(\varphi-90) & 0 \\ \sin(\varphi-90) & 0 & -\cos(\varphi-90) & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4) $$

$$ {}^{2}A_{3} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5) $$

The homogeneous transformation matrix (HTM) that expresses a point measured with the laser tracker with coordinates (x,y,z) in the fixed global coordinate reference system of the lower platform RS $_{Global}$ for each of the six platform different positions (1-6) with the following simplified equation (6) is calculated by means of the IMP mathematical model [21] as shown in equation 6.

$$ \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}_{SR_{Global}} = {}^{RS_{Global}}T_{RS_{UpperPlat}} \; {}^{RS_{UpperPlat}}T_{RS_{LT}} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}_{SR_{LT}} \quad (6) $$

The indexed metrology platform model uses the optimum platform geometric parameters found during its calibration and the readings of the capacitive sensors captured for each point measured with the laser tracker during the verification procedure of the laser tracker. For each point measured, a single homogeneous transformation matrix (HTM) that allows the transformation from the upper platform reference system RS $_{UpperPlat}$ to the global reference system RS $_{Global}$ located in the lower platform for the six platform positions is generated. The steps that will be followed in the verification procedure of the laser tracker with the indexed metrology platform are the following:

1. Assembling of the laser tracker on the indexed metrology platform.

2. Positioning of the platform in the position 1. Measure the three reference spheres of the upper platform with the laser tracker in order to obtain the homogeneous transformation matrix that links the laser tracker reference system RS $_{LT}$ and the upper platform reference system RS $_{UpperPlat}$, see Fig. 3.

3. Link geometrically the current reference system of platform position 1 with the global coordinate reference system RS $_{Global}$ by means of the capacitive sensor readings captured simultaneously to the point measured and the optimal geometrical parameters obtained in the platform calibration.

4. Measure the *n* retroreflectors in the reference mesh with the laser tracker from position 1 of the platform.

5. Obtain the homogeneous transformation matrix (HTM) that links the upper platform coordinate reference system and the global coordinate reference system for each of the *n* points measured in the reference mesh, see Fig. 3. The HTM will be unique for each point measured due to the small variation of position and orientation of the upper platform with respect to the lower platform, being controlled this variation with the capacitive sensors.

6. Rotate the platform to the position 2 and determine the geometric relationship between the current reference system with the global reference system of the fixed platform, using the capacitive sensors readings and the set of optimum geometrical parameters data from the calibration procedure.

7. Measure the *n* retroreflectors in the reference mesh from position 2 of the platform.

8. Repeat the procedure for obtaining the homogeneous transformation matrix that links upper and lower platform reference systems as explained in step 5, for all the retroreflectors measured from position 2 of the platform.

9. Repeat steps 6, 7 and 8 for each of the four remaining positions of the platform.

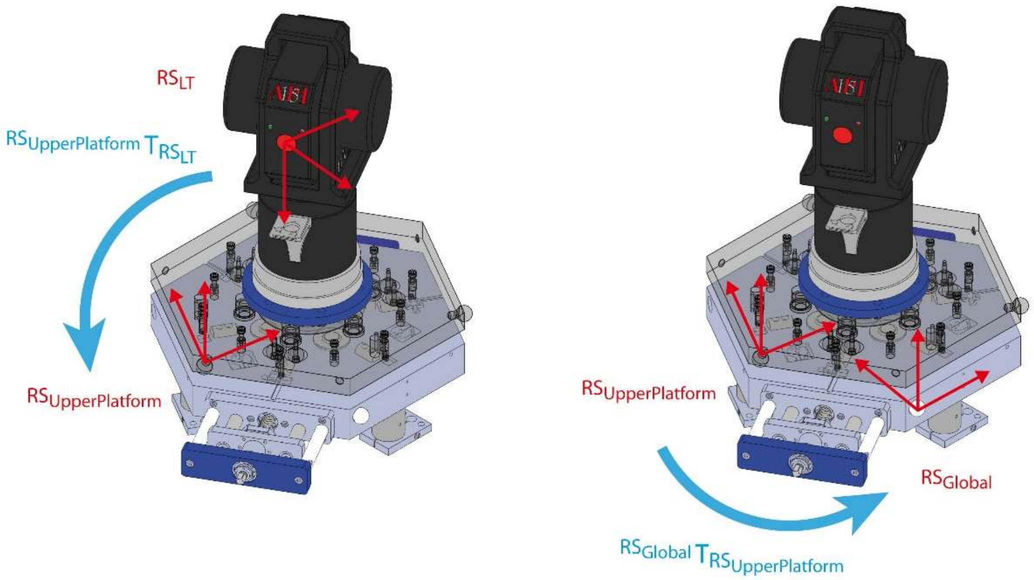


Fig. 3 Laser tracker API-T3-15 m, upper platform and lower platform coordinate reference systems

3. Laser tracker verification procedure with the indexed metrology platform.

Following the integration of the kinematic models of the laser tracker and the indexed metrology platform, the verification procedure to assess the volumetric performance of the laser tracker with the platform is developed. In this case, a retrorreflector mesh whose area materializes part of the working volume of the measuring instrument is used as a reference artifact. The laser tracker model used in the experimental testing is an API T3-15 m with angular accuracy of 3.5 µm/m, ADM accuracy of ± 15 µm and IFM accuracy of ± 0.5 ppm. The 27 surface mounted reflectors (SMR) distributed in the mesh are model Hallow 40M with 1.5" (38.1 mm) diameter y sphere roundness grade 50 ± 0.00005" (±1.3 µm).

The reflector mesh has a dimension of 6 x 6 x 6 m and the position of the targets were defined according to a sensitivity analysis [32] previously carried out in order to know how each individual position could affect to the global laser tracker error and determine the most sensitive positions to laser tracker error generation. The sensitivity analysis enables us to know how each individual error affects the measuring model of the laser tracker and identifies the testing positions that maximize the error generation. The measurement error was individually analyzed for each linear error (δx, δy, δz) and angular errors (εx, εy and εz) parameters on each simulation considering variables the elevation angle (77º -66º), the azimuth angle (1-360º) and the distance R (1-15 m) from the laser tracker to the SMRs. The analysis indicated that the SMR positions defined at minimum (-60º), zero and maximum (77º) elevation angle presented more sensitivity to error generation. In addition, the errors caused by the rotary errors in X and Y of the horizontal angle were also sensitive to this same rotation. Therefore these results were taken into account for the mesh's design. The SMRs were located at three different heights (6 m, 2 m, 0 m), see Table 2, corresponding to the elevation angles (77º, 0º, -66º) identified in the sensitivity analysis. The laser head rotation and inclination together with the distance to the laser tracker were evaluated and fixed in order to define the 27 retroreflectors positions distributed in the mesh, see Table 2. The laser tracker assembled on the indexed metrology platform is located at 1.5 m from the ground.

Table 2. Retroreflectors position in the measuring mesh

Retroreflector	Height	Retroreflector	Height	Retroreflector	Height
1	6 m	10	2 m	19	1 m
2	6 m	11	2 m	20	Ground
3	6 m	12	2 m	21	1m
4	6 m	13	2 m	22	Ground
5	6 m	14	2 m	23	1m
6	6 m	15	2 m	24 gauge	Ground
7	6 m	16	2 m	25 gauge	Ground
8	6 m	17	Ground	26 gauge	Ground
9	2 m	18	Ground	27 gauge	Ground

In Fig. 4 and Fig. 5 it could be observed the physical disposition of the retroreflectors in the mesh used in the verification procedure, together with their distances to the laser tracker considering a laser tracker height of 1.5 m.

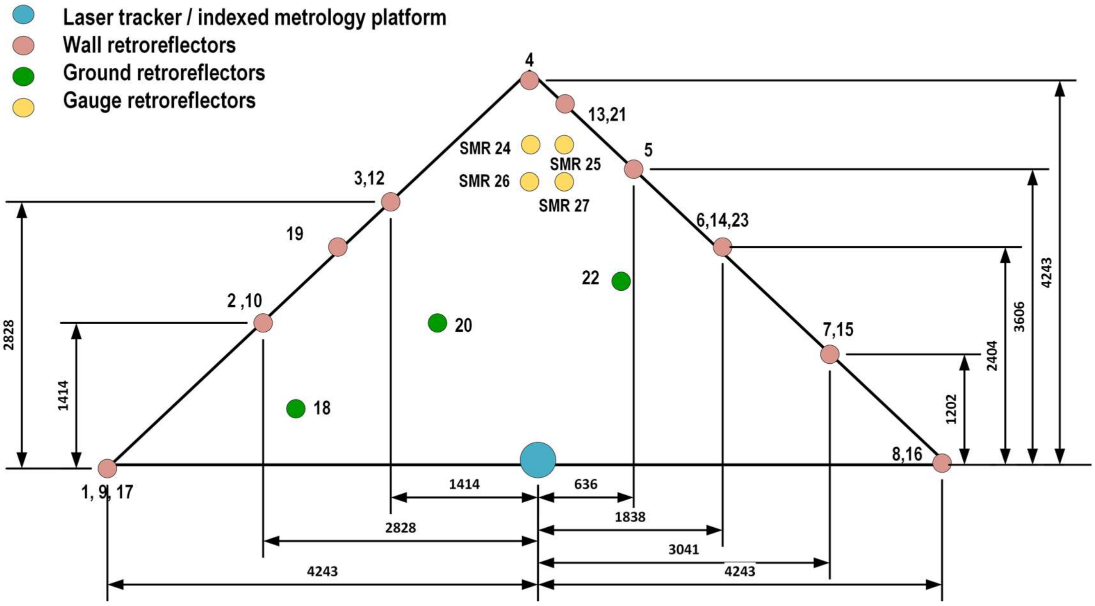


Fig. 4 Measuring mesh with retroreflectors position (1)

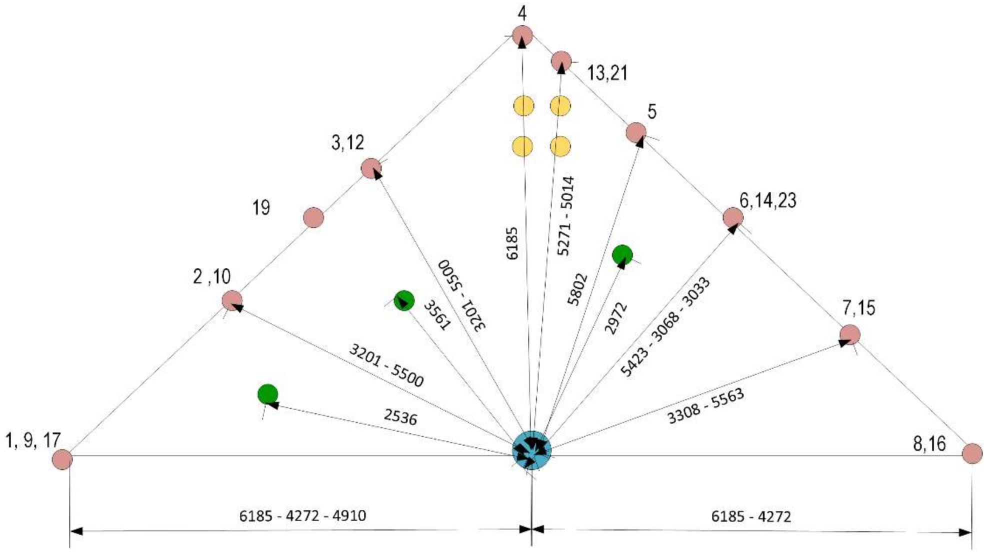


Fig. 5 Measuring mesh with retroreflectors position (2)

In the verification procedure, the laser tracker is assembled on the indexed metrology platform by means of a special designed fixture and rotates with the platform in the six platform positions corresponding to a rotation of 60 degrees, see Fig. 6. In the experimental procedure, the coordinate centers of the 27 retroreflectors were measured with the laser tracker, but taking into account the six platform positions, the number of mesh evaluated was six in total, each one composed of the 27 targets in the physical mesh. Each time the platform rotates to a new position allowing the laser tracker to measure the same target, a new working volume of the laser tracker is evaluated. The use of the laser tracker with the indexed metrology platform allows us to evaluate a greater number of mesh positions, concluding that the laser working volume could be satisfactorily explored. One of the main advantages of the indexed metrology platform is the possibility to express points in a global coordinate reference system RS_{Global}, permitting with its rotation to evaluate different laser tracker working volumes without the need of a new physical measuring mesh , which are normally big for high range measuring equipment.

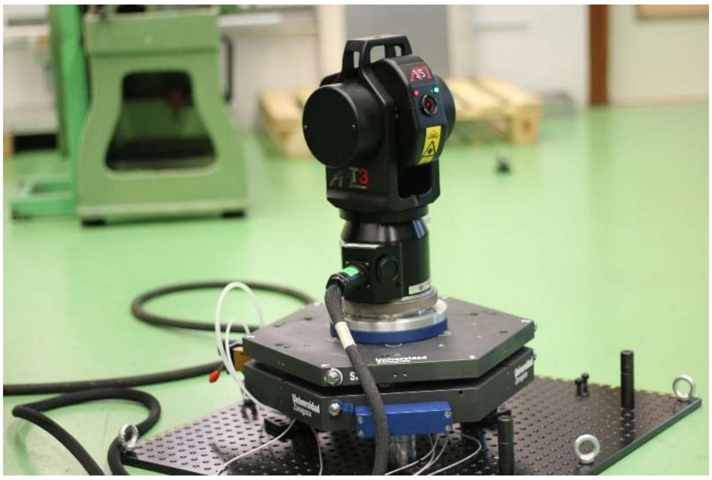


Fig. 6 Laser tracker with indexed metrology platform

In addition, a physical reference gauge composed of four retroreflectors (24-27) as shown in Fig. 7 was used in the verification procedure. This gauge developed as a first quick verification reference artifact, was considered as reference for defining the nominal calibrated distances included in the Table 3, which will be compared afterwards with the laser tracker measurement values. The nominal distances were measured with a coordinate measuring machine (CMM) located in the laboratory with a controlled temperature of 20ºC ± 0.1ºC. Table 4 presents the results obtained in the measurement of the physical gauge with the coordinate measuring machine.

Fig. 7 Retroreflector gauge and measurement with coordinate measuring machine

Table 3. Calibrated distance definition in retroreflector gauge

Retroreflector origin	SMR 24	SMR 25	SMR 26
	24-25	25-26	26-27
Distances	24-26	25-27	
	24-27		

Table 4. Gauge calibrated distances measured with coordinate measuring machine

Retroreflector origin	SMR 24	SMR 25	SMR 26
	357.6578	590.0766	355.9700
Distances (mm)	387.8870	386.8024	
	454.4279		

4. Experimental procedure.

The experimental procedure carried out in this work for the verification of the laser tracker with the indexed metrology platform starts with the laser tracker measurement of the three reference spheres located in the upper platform, generating in this case the homogeneous transformation matrix (HTM) that links the laser tracker reference system RS_{LT} with the upper platform reference system $RS_{UpperPlat}$. Next, the measurement with the laser tracker of the retroreflector mesh, including the physical gauge is carried out, beginning with the retroreflector 1 according to Table 2 and with the platform located in the position 1. This procedure is done for the rest of the platform positions (2-6) capturing the coordinate centers of the 27 retroreflectors with 500 data per point.

In parallel to the measurement of the reflectors, the readings of the capacitive sensors are captured per each measured point and platform position (1-6). The capacitive sensor readings are used to calculate the single homogeneous transformation matrix per point to change from the upper platform coordinate reference system $RS_{UpperPlat}$ to the global coordinate reference system RS_{Global} , expressing in this way a point captured by the laser tracker in the global reference system.

The coordinates of the reflectors centers measured with the laser tracker, together with the Euclidean distances between their centers, will be the parameters considered to evaluate the volumetric performance of the laser tracker. The locations of the reflectors in the measured mesh with the laser tracker and their coordinates expressed in laser tracker reference system RS_{LT} for each of the six platform positions are shown in the Fig. 8.

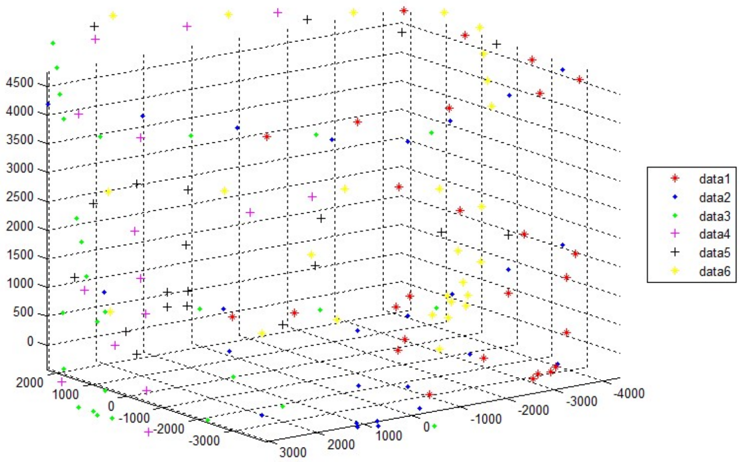


Fig. 8 Retroreflector center coordinates per measuring mesh (1-6) expressed in laser tracker reference system

Due to the ability of the indexed metrology platform to express points in its global coordinate reference system and considering the homogeneous transformation matrix calculated for each measured point and platform position, it is possible to express the 27 retroreflector measured coordinates centers in each mesh (1-6) corresponding to the six platform rotating positions, in the global platform reference system as shown in Fig. 9. In this case, it can be observed that the reflector coordinates for each platform position are very close, attributing their variation to the error included in the measurement procedure by the platform. These points' coordinates in the global reference system will be used during the verification procedure to evaluate the laser tracker error with the indexed metrology platform.

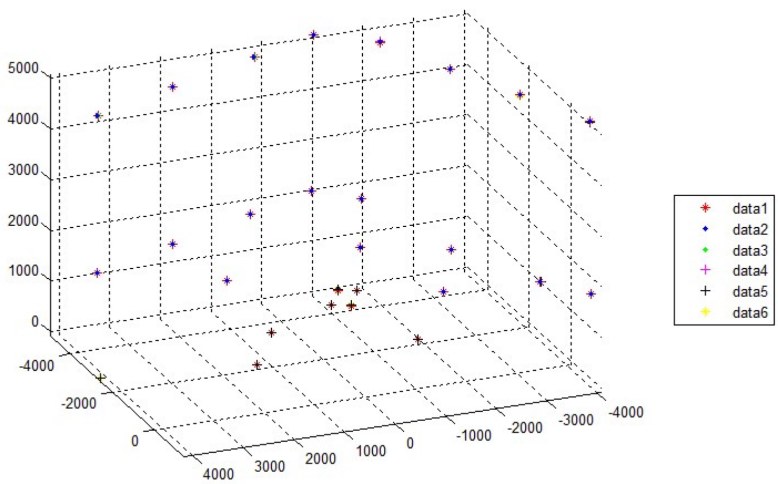


Fig. 9 Retroreflector center coordinates per measuring mesh (1-6) expressed in the global platform reference system

Once all the targets positions are captured with the laser tracker, an evaluation of the performance of the laser with the indexed metrology platform within its working volume is done. The applicable standards to laser tracker that define comparable evaluating criteria for this equipment are the American standard ASME B89.4.19 - 2006 [10], the technical recommendation VDI/VDE 2617-2011 part 10 [11] and the draft of ISO/CD10360-10 [12] standard. According to these standards, the evaluation of the volumetric performance of the laser tracker is specified in the length error test procedure, comparing the length error value obtained with the maximum permissible error given by the manufacturer. The measurements of the reference lengths materialized in this case by the physical gauge and the distances among the retroreflectors in the measuring mesh, are done with interferometer (IFM) or absolute distance measurement (ADM) placing the calibrated reference length in several positions and orientations. The laser tracker could be repositioned for each reference length if this could be easier than relocating the measuring line. In this work, the laser tracker remains fixed on the indexed metrology platform and rotates with the six platform positions, having also the calibrated gauge a static position. The SMR measuring mesh will be used in this verification procedure as a reference artifact. Using the indexed metrology platform it is possible to evaluate the measurement error through reproducibility or fixed point error tests carried out independently of the laser tracker's error source. The platform enables us to know with high accuracy the position from the upper platform with respect to the lower platform where the global coordinate reference system is located. The parameters that will be used in this work for assessing the volumetric error of the laser tracker with the indexed metrology platform are following described in detail.

- *Distance reproducibility evaluation per platform position.*

As a first step, for each platform position (1-6) the Euclidean distances among the 27 retroreflector centers were calculated generating 351 distances between centers per platform position. Therefore, 351 distance errors per platform position were obtained comparing the distances in the platform position 1 taken as reference to the distances obtained in the platform positions (2-6). The parameters calculated were a mean distance error and a maximum distance error among all the platform positions measured. These values go further from a conventional repeatability that could be obtained measuring several times the same mesh from a fixed laser tracker and platform position. In this case, the indexed metrology platform and the laser tracker rotate together, therefore the error obtained with this evaluation method should be bigger than the one out of a conventional laser tracker repeatability evaluation. Nevertheless, it is worth mentioning that the influence of the platform in the verification procedure is insignificant in comparison with the laser tracker error.

- *Volumetric accuracy evaluation.*

The volumetric performance of the laser tracker is evaluated by means of a distance error or distance deviation. The distance deviation is calculated as shown in equation (7), where L_i is the distance between the retroreflector centers measured with the laser tracker and L_{Cal} the calibrated distance. In this procedure, the measurements made on the gauge with a coordinate measuring machine with the result values listed in the Table 4 will be considered as the calibrated distances.

$$D_i = L_i - L_{Cal} \qquad (7)$$

In this case, six distances between the centers of the retroreflectors located in the gauge will be calculated, see Table 3. As a final result of this test, three parameters are obtained, the maximum distance deviation among tests positions, 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 equation (8).

$$2RMS = 2\sqrt{\frac{\sum Di^2}{n}} \qquad n=36 \qquad (8)$$

- *Fixed point error evaluation.*

As mentioned before, one of the main advantages of the indexed metrology platform is its ability for expressing points in a global coordinate reference system by means of the platform mathematical model. On these grounds, the fixed point error evaluation is based on the calculation of the Euclidean distance between the coordinates of a retroreflector in two different platform positions, taking as reference position one of the platform. The point coordinates measured with the laser tracker in different platform positions but expressed in the platform global reference system should be the same, since the platform itself should not affect this result in a theoretical approach. The parameters calculated as a result in this evaluation are the mean and maximum fixed point error.

As a previous step and in order to evaluate the suitability of the indexed metrology platform as an auxiliary equipment for portable measuring coordinate machines like AACMMs or laser trackers, an estimation of the indexed metrology platform's uncertainty using the Monte Carlo method, considering the complex mathematical model of the platform, was developed. Firstly, it was necessary to define and select the model's input variables which could affect the output variable. The possible error sources that may influence the indexed metrology platform's uncertainty were identified - the platform calibration's uncertainty, the capacitive sensors' error, the error of the portable measuring equipment that will be used with the platform, the temperature and the dynamic behavior of the platform during the measuring process. Considering 10000 iterations in the Monte Carlo simulation and an AACMM as measuring instrument, the mean, uncertainty and confidence interval values for the output variables were calculated. The n-homogeneous transformation matrices (XYZABC) that allow the change of reference systems from the upper platform coordinate reference system to the lower platform or global coordinate reference system were considered as output variables of the IMP's mathematical model. The indexed metrology platform position and orientation uncertainty for a given platform position and point measured on a ball bar gauge sphere with the AACMM is presented in Table 5:

Table 5. Indexed metrology platform position and orientation uncertainty in homogeneous transformation matrices upper to lower platform, sphere 1, point 1, n-iterations 10000

$^{RS\ Global}T_{RS\ UpperPlat}$ *(Sphere 1 / Point 1 / Platform position 1)*			
	Nominal	**Mean**	**Uncertainty** (µm / º)
X (mm)	-0.13500	-0.13502	0.01996
Y (mm)	196.61710	196.61707	0.04489
Z (mm)	40.84180	40.84181	0.04965
A (º)	179.99880	179.99879	0.02057
B (º)	0.01940	0.01941	0.01677
C (º)	60.05620	60.05621	0.01159

Based on these n-homogeneous transformation matrices obtained in the Monte Carlo simulation and considering the possibility of expressing points in a global coordinate reference system located in the lower platform base, it is possible to estimate the IMP's uncertainty in a distance measurement between pairs of the n-sphere's centers, simulated in the global platform coordinate reference system. Two reference calibrated distances were defined, d12 = 100.80247 mm and d15= 399.96137 mm to calculate the distance error as difference between the distance obtained in the Monte Carlo simulation and the calibrated distance value. The IMP's uncertainty values obtained in a distance measurement are shown in Table 6, which confirms the correct operation of the IMP as an auxiliary instrument for laser trackers or AACMM verification procedures due to the accuracy range needed.

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

5. Results

In Fig. 10, 11, 12, 13 and 14, the error vectors corresponding to the coordinates of the 27 retroreflectors measured and expressed in the global platform reference system for the six platform positions are represented. The mesh 1 was taken as a reference and corresponds to the laser tracker measurements carried out from the platform position 1, being the same criteria applied for the rest of the platform positions. In all the cases it could be observed the same random tendency between the coordinates of the same retroreflector measured from two different mesh.

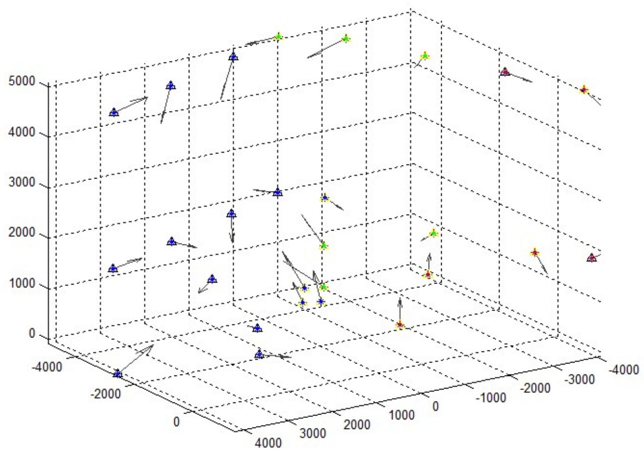


Fig. 10 Reflector coordinate error vectors mesh 1 and mesh 2 (amplifying factor 50).

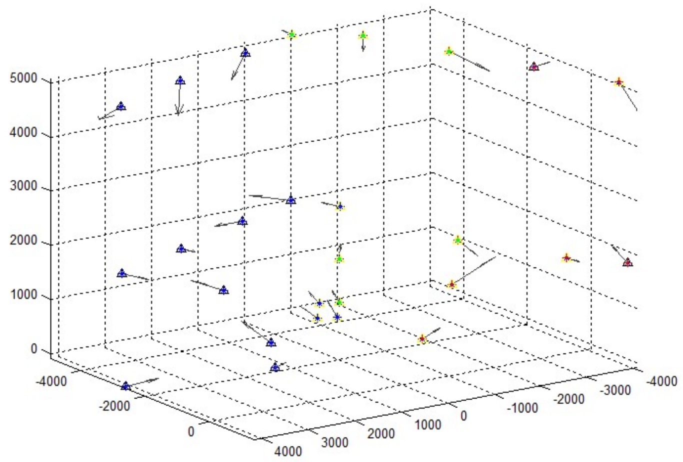


Fig. 11 Reflector coordinate error vectors mesh 1 and mesh 3 (amplifying factor 50).

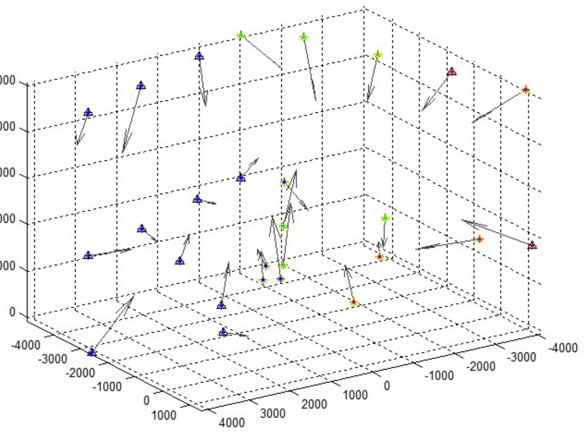


Fig. 12 Reflector coordinate error vectors mesh 1 and mesh 4 (amplifying factor 50).

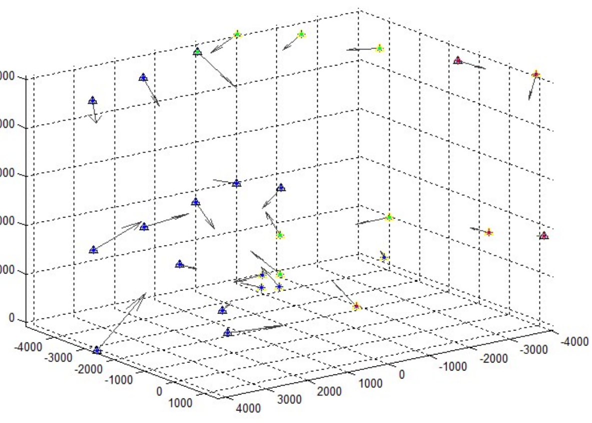


Fig. 13 Reflector coordinate error vectors mesh 1 and mesh 5 (amplifying factor 50).

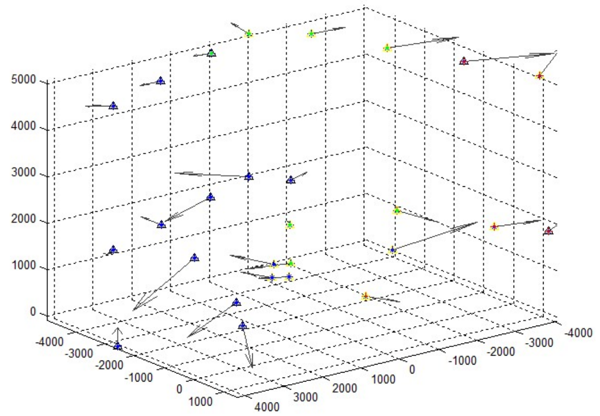


Fig. 14 Reflector coordinate error vectors mesh 1 and mesh 6 (amplifying factor 50).

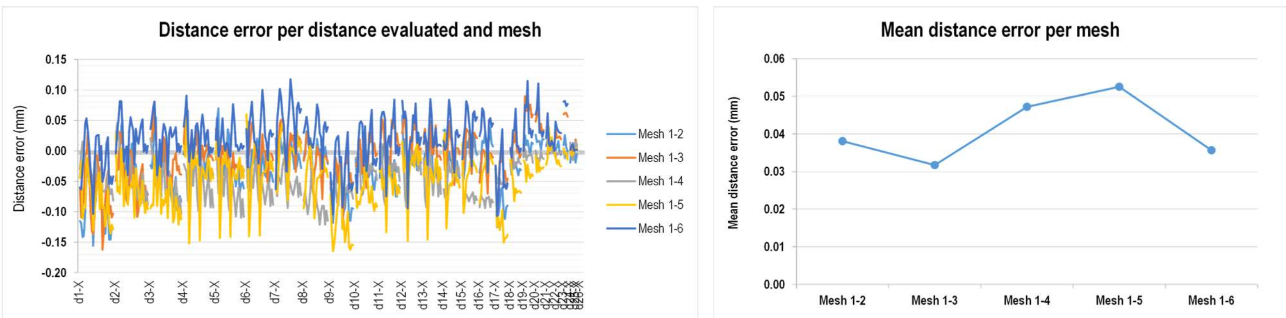
5.1. Distance reproducibility evaluation per platform position

The evaluation parameters of the laser tracker - indexed metrology platform distance reproducibility are based on the distance error calculation obtained after comparing the 351 distances between the retroreflectors in platform position 1 with the same distances obtained in the rest of platform positions (2-6). The mean and maximum error values obtained were 0.0410 mm and 0.1651 mm as shown in Table 7.

Table 7. Laser tracker with indexed metrology platform distance reproducibility error

	Laser tracker and indexed metrology platform
Mean distance reproducibility error (mm)	0.0410
Maximum distance reproducibility error (mm)	0.1651

The 351 distance error values obtained from comparing the distances measured in the platform position 1 (mesh 1) with the distances obtained in the rest of the platform positions (mesh 2-6) are shown in Fig. 15 (a). Five data series are generated for each of the measurements made by the laser tracker on each platform position taken as reference the measurements made in the platform position 1 (mesh 1). In addition, it could be seen in the Fig. 15 (b) the mean distance error values per mesh, taking as reference the platform position 1 (mesh 1). It could be observed that the distance error shows its highest value for the platform positions 5 corresponding to a 240º azimuthal rotation of the platform and laser tracker.



(a) (b)

Fig. 15 Distance reproducibility errors per measuring mesh

5.2. Volumetric accuracy evaluation per platform position

In the volumetric performance evaluation of the laser tracker with the indexed metrology platform, the distance error between retroreflectors centers measured in the gauge shown in Fig. 7 is calculated, where the error value is obtained as the difference between the measured and the calibrated length in the gauge. The resulted parameters included in Table 8 are the mean distance deviation, the maximum distance deviation among tests positions, the range of the distance deviations and the 2RMS. These values are calculated considering as calibrated values the gauge measurements made with a coordinate measuring machine (CMM). The mean distance error, maximum distance error, range of distances and 2RMS values obtained are 0.0650 mm, 0.1768 mm, 0.1595 mm and 0.1750 mm respectively.

Table 8. Laser tracker with indexed metrology platform volumetric performance results comparison

	CMM Measurement
Mean distance deviation (mm)	0.0650
Maximum distance deviation (mm)	0.1768
Range of distance deviations (mm)	0.1595
2RMS (mm)	0.1750

The distance errors defined according to Table 3 which are determined from the evaluation of the laser tracker measurements for each platform positions (1-6) are described in Fig. 16, considering as calibrated distances the ones measured on the gauge with a coordinate measuring machine shown in Table 4. The highest distance error values with both techniques are the ones corresponding to the reference length between the reflectors 26 and 27 with the disposition in the gauge shown in the Fig. 4.

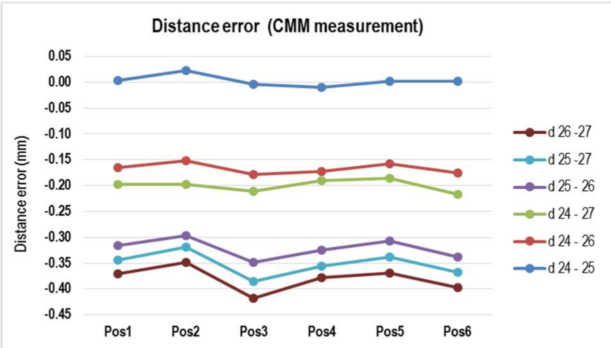


Fig. 16 Distance errors versus calibrated values measured with CMM per platform position

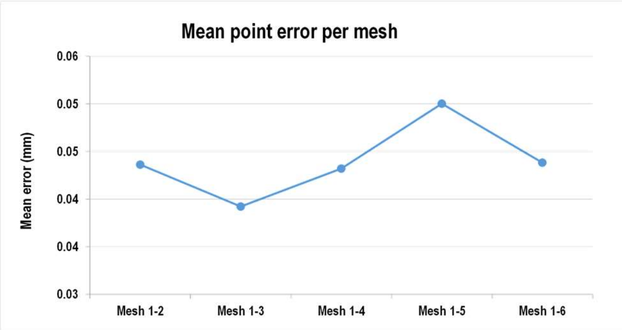
5.3. Fixed point evaluation per platform position

The fixed point error evaluation is based on the ability of the platform to express the same point coordinates in a global coordinate system by means of a the laser tracker for different platform positions, having ideally the same point measured from different platform positions the same coordinates. The fixed point error shows the difference between these coordinates measured with the laser tracker assembled on the indexed metrology platform from different platform positions. The values obtained in the evaluation are shown in the Table 9.

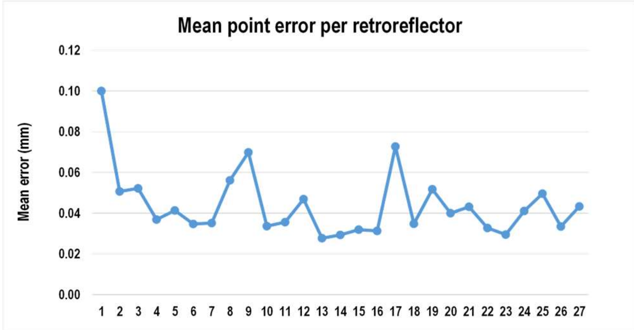
Table 9. Laser tracker with indexed metrology platform fixed point error

	Laser tracker and indexed metrology platform
Mean fixed point error (mm)	0.0439
Maximum fixed point error (mm)	0.1296

The mean and maximum error values are 0.0439 mm and 0.1296 mm. Fig. 17 (a) shows the mean fixed point error value per mesh (1-6) corresponding to the measurements made from each of the six platform rotating positions taking as reference the measurements made from platform position 1 (mesh 1). The biggest error value is obtained for the position 5 corresponding to a 240º azimuthal angle rotation of the platform. In addition, Fig. 17 (b) shows the mean fixed point error value for all the retroreflectors (1-27) in the measuring mesh among all the measurements made from the six platform positions. The retroreflectors with higher error values are 1, 9, 17 and 19. Considering the retroreflectors position in the mesh shown in the Fig. 4 and the Fig. 5, the reflectors number 1, 9 and 17 are located in the left corner of the retroreflector mesh where the laser tracker angle to the reflector generates a complicated measurement of the retroreflector. The retroreflector 19 which also shows a high error value, is located at 1 m height but it is also in the left corner of the measuring mesh .



(a)



(b)

Fig. 17 Mean fixed point error evaluation per mesh and retroreflector

6. Conclusions

In this work a new verification procedure of a laser tracker model API T3- 15 m assembled on an indexed metrology platform was developed. The first task previous to the development of the verification procedure, was the definition of the kinematic model of the laser tracker applying the Denavit – Hartenberg model and determination of the initial values for the model parameters. In the case of the indexed metrology platform, it was considered its mathematical model that generates the homogeneous transformation matrix per point measured that changes from the upper platform reference system to the global reference system located in the upper platform. Finally, we concluded with the integration of both mathematical models from laser tracker and platform, which allows to express the coordinates of a measured point with the laser tracker in the global reference system of the indexed metrology platform independently of its position.

In order to develop the laser tracker verification procedure, a measuring mesh of big dimensions integrated by 27 retroreflectors was used. This mesh was measured from the six platform position and generating in this way six measuring mesh. Once the positions of the retroreflector centers were captured by the laser tracker assembled on the platform, an analysis and evaluation of the error performed by the laser tracker in the verification procedure with the indexed metrology platform was carried out evaluating the following parameters: distance reproducibility per position, volumetric accuracy and fixed point error.

The 351 distance errors between the retroreflectors center coordinates determined from comparing the reference lengths defined in position 1 of the platform and the same reference lengths in the platform positions (2-6), allow to calculate mean and maximum distance reproducibility error values of 0.0410 mm and 0.1651 mm respectively. This *distance reproducibility values* estimates the error performed by the laser tracker from the same physical rotation position of the platform, measuring a set of reference lengths located in the same physical mesh, therefore it should not be affected by the rotation of the platform but by the uncertainty of the platform due for example to the capacitive sensor measurement. The *volumetric error* was obtained as a deviation between the reference lengths materialized by two retroreflector in a gauge measured with the laser tracker and the calibrated distance, considering as calibrated distance the same reference length measured with a coordinate measuring machine. The mean distance error, maximum distance error and range of deviations values obtained were 0.0650 mm, 0.1768 mm and 0.1595 mm. Finally the fixed point error evaluation objective is to evaluate that the coordinates of a point measured with the laser tracker and expressed in the platform global coordinate reference system are the same in all the platform positions, since the indexed metrology platform introduces ideally no error in the measuring process. The mean fixed point error value obtained was 0.0439 mm.

The results obtained allow to validate the correct use of the indexed metrology platform in verification procedures for laser tracker, pointing out its main advantage of expressing points in a global coordinate reference system RS_{Global}. This is a key point for high range measuring instrument calibration and verification procedures optimization, due to the fact that the platform rotation enables the evaluation of different laser tracker working volumes without the need of a new physical measuring mesh definition, decreasing as a result the testing time of the equipment and test positions to be defined which is of great importance for high range measuring instruments.

7. Acknowledgments

The support of Consejo Nacional de Ciencia y Tecnología (Concayt) of México is deeply acknowledged by the fourth author.

8. Bibliography

[1] K. Lau, R. Hocken, and L. Haynes, "Robot performance measurements using automatic laser tracking techniques," *Robot. Comput. Integr. Manuf.*, vol. 2, no. 3–4, pp. 227–236, Jan. 1985.

[2] W. C. Lau, K., Hocken, R. J., & Haight, "Automatic laser tracking interferometer system for robot metrology," *Precis. Eng.*, vol. 8, no. 1, 1986.

[3] A. Nubiola, M. Slamani, A. Joubair, and I. a. Bonev, "Comparison of two calibration methods for a small industrial robot based on an optical CMM and a laser tracker," *Robotica*, vol. 32, no. 03, pp. 447–466, 2013.

[4] K. C. Hocken, R. J., & Lau, "Three and five axes laser tracker systems," US4714339 A1987.

[5] P. G. Maropoulos, Y. Guo, J. Jamshidi, and B. Cai, "Large volume metrology process models: A framework for integrating measurement with assembly planning," *CIRP Ann. - Manuf. Technol.*, vol. 57, no. 1, pp. 477–480, Jan. 2008.

[6] S. Aguado, D. Samper, J. Santolaria, and J. J. Aguilar, "Identification strategy of error parameter in volumetric error compensation of machine tool based on laser tracker measurements," *Int. J. Mach. Tools Manuf.*, vol. 53, no. 1, pp. 160–169, Feb. 2012.

[7] J. Sładek, K. Ostrowska, P. Kohut, K. Holak, A. Gąska, and T. Uhl, "Development of a vision based deflection measurement system and its accuracy assessment," *Meas. J. Int. Meas. Confed.*, vol. 46, no. 3, pp. 1237–1249, 2013.

[8] J. Ouyang, W. Liu, X. Qu, Y. Yan, Z. Liang, and H. Province, "Modeling and self calibration of laser tracker using planar constraints," pp. 1–4.

[9] J. F. Ouyang, W. L. Liu, D. X. Sun, Y. G. Yan, and J. City, "Laser Tracker Calibration Using Coordinate Measuring Machine," pp. 5–8, 2005.

[10] American Society of Mechanical Engineers, "ASME B89.4.19-2006, Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems." pp. 1–76, 2006.

[11] Verein Deutscher Ingenieure, "VDI/VDE 2617 Part 10. Acceptance and reverification tests of laser tracker," no. January. pp. 1–36, 2011.

[12] International Organization for Standardization, "ISO / CD 10360-10 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMS) — Part 10 : Laser trackers for measuring point-to-point distances," 2012.

[13] B. Muralikrishnan, D. Sawyer, C. Blackburn, S. Phillips, C. Shakarji, E. Morse, and R. Bridges, "Choosing Test Positions for Laser Tracker Evaluation and Future Standards Development."

[14] B. Muralikrishnan, D. Sawyer, C. Blackburn, S. Phillips, B. Borchardt, and W. T. Estler, "ASME B89.4.19 Performance Evaluation Tests and Geometric Misalignments in Laser Trackers," *J. Res. Natl. Inst. Stand. Technol.*, vol. 114, no. 1, p. 21, Jan. 2009.

[15] B. Hughes, A. Forbes, A. Lewis, W. Sun, D. Veal, and K. Nasr, "Laser tracker error determination using a network measurement," *Meas. Sci. Technol.*, vol. 22, no. 4, p. 045103, Apr. 2011.

[16] B. Muralikrishnan, C. Blackburn, D. Sawyer, and S. Phillips, "Measuring scale errors in a laser tracker's horizontal angle encoder through simple length measurement and two-face system tests," *J. Res. Natl. Inst. Stand. Technol.*, vol. 115, no. 5, pp. 291–301, 2010.

[17] G. Gassner and R. Ruland, "Laser Tracker Calibration - Testing the Angle Measurement System," *Slac-Pub-13476*, no. December 2008, pp. 1–10, 2008.

[18] K. M. Nasr, B. Hughes, A. Forbes, and A. Lewis, "Determination of Laser Tracker Angle Encoder Errors," *Metrologie*, vol. 0002, pp. 0–3, 2013.

[19] E. Morse and V. Welty, "Dynamic testing of laser trackers," *CIRP Ann. - Manuf. Technol.*, vol. 64, no. 1, pp. 475–478, 2015.

[20] R. Acero, A. Brau, J. Santolaria, and M. Pueo, "Verification of an articulated arm coordinate measuring machine using a laser tracker as reference equipment and an indexed metrology," *MEASUREMENT*, 2015.

[21] A. Brau Avila, J. Santolaria Mazo, and J. J. Aguilar Martín, "Design and mechanical evaluation of a capacitive sensor-based indexed platform for verification of portable coordinate measuring instruments.," *Sensors (Basel).*, vol. 14, no. 1, pp. 606–33, Jan. 2014.

[22] H. R. Denavit J, "A kinematic notation for lower-pair mechanisms based on matrices," *J. Appl. Mech. ASME*, vol. 77, pp. 215–221, 1955.

[23] M. Hayati, S; Mirmirani, "Improving the absolute positioning accuracy of robot manipulators," *J. Robot. Syst.*, pp. 397–413, 1985.

[24] S. Hayati, K. Tso, and G. Roston, "Robot geometry calibration," *Proceedings. 1988 IEEE Int. Conf. Robot. Autom.*, pp. 947–951, 1988.

[25] T.-W. H. L. J. Everett, "The Theory of Kinematic Parameter Identification for Industrial Robots," *J. Dyn. Syst. Meas. Control*, vol. 110, no. 1, 1986.

[26] C. Veitschegger, W.K. Wu, "A Method for Calibration and Compensationg Robot Kinematic Errors," in *Proceedines of the 1987 IEEE International Conference on Robotics and Automation*, 1987, pp. 39–44.

[27] C. Veitschegger, W.K. Wu, "Robot Accuracy Based on Kinematics," *IEEE J. Robot. Autom.*, vol. RA-2, pp. 171–179, 1986.

[28] C. Veitschegger, W.K. Wu, "Robot Accuracy Analysis," in *Proceedings of the 1985 IEEE Conference on Cybernetics*, 1985, pp. 425–430.

[29] L. Everett, M. Driels, and B. Mooring, "Kinematic modelling for robot calibration," *Proceedings. 1987 IEEE Int. Conf. Robot. Autom.*, vol. 4, pp. 183–189, 1987.

[30] P. D. Lin and C.-H. Lu, "Modeling and Sensitivity Analysis of Laser Tracking Systems by Skew-Ray Tracing Method," *J. Manuf. Sci. Eng.*, vol. 127, no. 3, p. 654, 2005.

[31] K. M. Nasr, A. B. Forbes, B. Hughes, and A. Lewis, "ASME B89.4.19 standard for laser tracker verification – experiences and optimisations," *Int. J. Metrol. Qual. Eng.*, vol. 3, no. 2, pp. 89–95, Nov. 2012.

[32] A. C. Majarena Bello, J. Conte Blasco, R. Acero Cacho, J. Santolaria Mazo, and A. Brau Ávila, "Estrategias de modelado cinemático e identificación de parámetros de láser trackers," in *XX Congreso Nacional de Ingeniería Mecánica*, 2014, p. 193.