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Identification and kinematic calculation of Laser Tracker errors

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Abstract

Calibration of Laser Tracker systems is based most times in the determination of its geometrical errors. Some standards as the ASME B89.4.19 (2006) and the VDI 2617-10 (2011) describe different tests to calculate the geometric misalignments that cause systematic errors in Laser Tracker measurements. These errors are caused not only because of geometrical misalignments and other sources of error must also be taken in count. In this work we want to express the errors in a kinematic form. Errors will be split in two different components, geometric and kinematic errors. The first ones depend on the offsets, tilts and eccentricity of the mechanical and optical components of the system. Kinematic errors are different for every position of the Laser tracker, so they must be formulated as functions of three system variables: range (R), vertical angle (V) and horizontal angle (H). The goal of this work is to set up an evaluation procedure to determine geometric and kinematic errors of Laser Trackers.

Keywords: Laser tracker; calibration; kinematic errors; synthetic generator.

1. Introduction

The importance of accuracy in Laser Tracker Systems (LT) is its function as a standard measurement for a wide range of equipment and facilities. The scope of the present work is to establish a verification procedure and simplified calibration method to correct the errors caused in the LT on a regular measuring range. The procedure will be based both on measurements of patterns with known and calibrated distances and the measurement of a mesh of reflectors placed at unknown locations looking to reduce the time and cost of testing and calibrating of the

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equipment. In addition, the mathematical model of the LT will be determined obtaining its kinematic parameters; by one hand considering its model error and by the other throughout uncertainty assessment techniques based on Monte Carlo method and considering the influence of the error sources. This simulation will establish a priori the better conditions for capture points, ie leading to a lower measurement uncertainty in points captured. Because of the large number of sources of error to be considered in this type of equipment, an approximation of these features will, before capture, offer an optimum manner the position of LT in the capture procedure and the sequence and point to check.

2. Laser Tracker measuring principle

The LT is a measuring instrument that tracks the movement of a reflector and calculates its position in spherical coordinates. The distance to the reflector (d) can be measured by an interferometer (IF) or by an absolute distance meter (ADM), while the inclination angles (φ) and azimuthal (θ) are measured by two angular encoders. The reflector returns the laser beam, where the beam strikes a position sensor (PSD) that detects any change in position causing the movement of the axes of LT so that the laser beam is incident on the optical center of the reflector. Thus the LT head constantly monitors the position of the reflector. There are also reflectors mounted on rotating devices with two degrees of freedom which can also follow the LT beam, which allow the simultaneous movement of the emitter and reflector so that both seek its correct alignment. This expands the measurement possibilities with moving equipment (machine tools, robots) without need for multiple reflectors or interrupt the measurement process to move or redirect the spotlight.

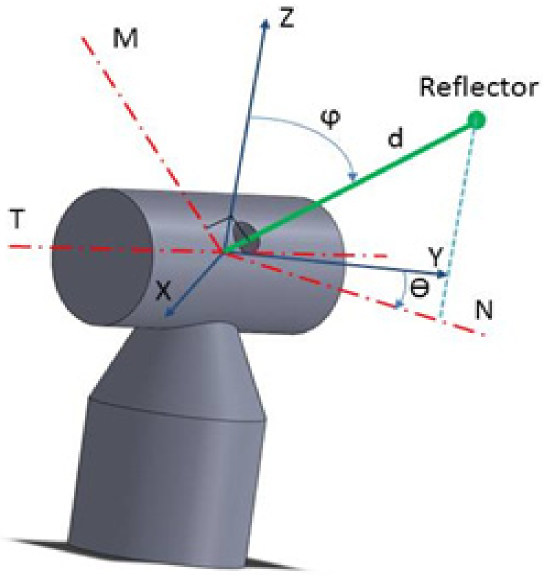

Fig. 1. Laser Tracker measuring principle.

Having the spherical coordinates, it’s possible to obtain the cartesian coordinates of the reflector with respect to the reference source of LT with equations 1 to 3:

(1)

(2)

$$z = d \times \cos(\theta) \quad (3)$$

These are the nominal values corresponding to a perfect LT, equipment calibration will give the correction parameters needed to correct these values by modeling errors.

3. Laser Tracker models

There are different commercial brands in the market selling LT equipment each one with its particular characteristics. This makes the kinematic modeling of each one of them to be different, not being able to establish a unique model.

It is possible to classify all existing LT models in two families, depending on the origin of the laser beam; from the rotating head of the LT or in the column holder with a mirror reflector in the rotating head. The kinematic model is different in both cases since the system reference source is different between them as well as the influence of the geometry measurement errors.

3.1 Laser Tracker with beam source in the rotating head

This model is typical of API and FARO and determination of their geometric errors has been systematized by Muralikrishnan et al. (2009) and Hughes et al. (2011). According to the proposed model, calibration corrections are based on 15 parameters, each representing the influence of a particular geometric error in the overall error of the equipment:

- Beam Offset (x1): displacement of the point of emission of the laser beam with respect to the reference system origin. Is divided into two components: x_{1t} and x_{1m} which are determined projecting x_1 on the tilt axis (T) of the TL and the axis normal to the tilting axis and the laser beam (M).
- Transit Offset (x_2): tilt axis displacement (T) with respect to azimuth (Z).
- Vertical Offset Index (x_3): zero offset vertically encoder.
- Beam Tilt (x_4): inclination of the laser beam with respect to its nominal trajectory perpendicular to the tilt axis (T). Is decomposed into its projections on the tilt axis (x_{4t}) and the beam perpendicular to the beam (x_{4m}). The latter is not considered for having the same meaning as x_3.
- Transit Tilt (x_5): error of perpendicularity between the tilt axis (T) and the azimuth (Z).
- Encoder Eccentricity (x_6 and x_7): eccentricity errors of horizontal and vertical encoders. They are divided into components X, Y for the azimuthal (x_{6x}, x_{6y}) and Z and N components (beam projection on the XY plane) for the tilt (x_{7n}, x_{7z}).
- Bird Bath Error (x_8): calibration error in the distance to the birthplace of the reflector.
- Errors in the Encoder Scale (x_9 and x_{10}): Errors of scale in horizontal and vertical encoders.

This set of parameters correct the measured values (Rm, Hm, Vm) for the actual measurements (Rc, Hc, Vc) with equations 4 to 6:

$$R_c = R_m + x_2 \cdot \sin(V_m) + x_8 \quad (4)$$

$$H_c = H_m + \frac{x_{1t}}{R_m \cdot \sin(V_m)} + \frac{x_{4t}}{\sin(V_m)} + \frac{x_5}{\tan(V_m)} + x_{6x} \cdot \cos(H_m) - x_{6y} \cdot \sin(H_m) + x_{9a} \cdot \sin(2 \cdot H_m) + x_{9b} \cdot \cos(2 \cdot H_m) \quad (5)$$

$$V_c = V_m - \frac{x_{1m}}{R_m} + \frac{x_2 \cdot \cos(V_m)}{R_m} + x_3 + x_{7n} \cdot \cos(V_m) - x_{7z} \cdot \sin(V_m) + x_{10a} \cdot \sin(2 \cdot V_m) + x_{10b} \cdot \cos(2 \cdot V_m) \quad (6)$$

3.2 Laser Tracker with beam source column

LT model used by Leica and whose geometric error model was set by Loser et al. (1999). Geometric errors are similar to those from the previous model but with the particularity that the laser beam that emerges from the column in the vertical direction LT, is directed to the reflector by a mirror whose center of rotation coincides with the nominal theoretical intersection of the azimuth and tilt axes. The errors described are:

- Transit Axis Offset (e) displacement of the tilting axis with respect to the azimuth.
- Mirror Offset (f) mirror plane displacement with respect to its nominal rotation center.
- Beam Offset (O_1): displacement of the laser beam with respect to the vertical axis into components X, Y (O_{1x}, O_{1y}).
- Offset Plate Cover (O_2): displacement of the laser beam with respect to the vertical axis due to refraction at the crystal output into its components X, Y (O_{2X}, O_{2y}).
- Mirror Tilt (c) mirror tilt about the tilt axis (T).
- Transit Axis tilt (i): error of perpendicularity between the tilt axis (T) and vertically (Z).
- Beam Axis tilt (I): laser beam tilt about the vertical axis (Z) into its components X, Y (I_x, I_y).
- Horizontal Encoder Eccentricity (E): horizontal encoder eccentricity components X, Y (E_x, E_y).
- Vertical Encoder Eccentricity (K): vertical encoder eccentricity components Z, N (K_z, K_N).
- Vertical Offset Index (j): error angular position (inclination 90 °) Vertical encoder.

This set of parameters correct the measured values (Rm, Hm, Vm) for the actual measurements (Rc, Hc, Vc) with equations 7 to 9:

$$R_c = R_m - 2 \cdot \sin\left(\frac{V_m}{2}\right) \cdot \left(e \cdot \cos\left(\frac{V_m}{2}\right) + f\right) \quad (7)$$

$$H_c = H_m + \frac{1}{\sin(V_m)} \cdot \left[I_x \cdot \cos(H_m) - I_y \cdot \sin(H_m) + \frac{O1_x \cdot \cos(H_m) - O1_y \cdot \sin(H_m) + O2_x + H_{off}}{R_m}\right] - \frac{i \cdot \sin\left(\frac{V_m}{2}\right) + c}{\cos\left(\frac{V_m}{2}\right)} + E_y \cdot \sin(H_m) - E_x \cdot \cos(H_m) \quad (8)$$

$$V_c = V_m - \left[I_x \cdot \sin(H_m) + I_y \cdot \cos(H_m)\right] - \frac{O1_x \cdot \sin(H_m) + O1_y \cdot \cos(H_m) + O2_y + V_{off}}{R_m} - \cos\left(\frac{V_m}{2}\right) \cdot \left[\frac{2}{R_m} \cdot \left(e \cdot \cos\left(\frac{V_m}{2}\right) + f\right) + K_z\right] + K_N \cdot \sin\left(\frac{V_m}{2}\right) \quad (9)$$

H_{off} and V_{off} terms are characteristic PSD's errors

4. Kinematic model

Correction parameters of both models are always LT distances, angles and proportionalities, which can be represented in matrix form as changes of reference frame representing the distance or angle or corresponding proportionality. Thus we can consider the laser beam as an open kinematic chain whose joints are the points at which errors occur. In this way we can represent the nominal kinematic modeling of LT following Denavit-Hartenberg (1955) method modified by Hayatti-Mirmirani (1985), introducing a number of error matrices correcting the nominal model based on the error parameters. This requires formulating the kinematic chain properly so that the beam path follow in order them kinematic chain.

5. Laser Tracker modeling errors with beam source in the head (Model 1)

The first model is the simplest one, since the origin of the beam coincides with the theoretical intersection of the axes of rotation of the head, which means that there is no displacement between the origins of reference systems for each joint being easier the definition of the nominal kinematic model.

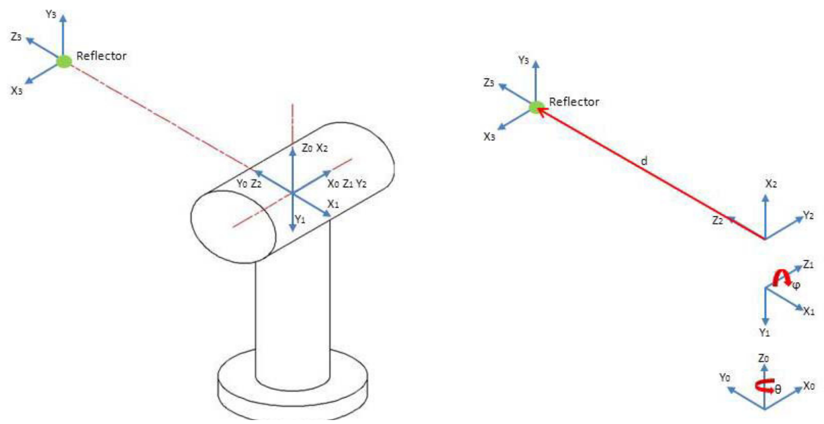

Fig. 2. Model 1 Kinematic Parameters.

According to the frame systems criteria established in Figure 2, the kinematic model will be as shown in Table 1.

Table 1. Model 1 Kinematic Parameters

	θi	αi	Ai	di
1	Θ-90	-90	0	0
2	ϕ-90	90	0	0
3	-90	0	0	d

The transformation matrix between two consecutive reference frames j-1 and j is obtained on the base of the kinematic parameters as the product of translation and rotation matrices which depend on them:

$$ {}^{j-1}A_j = T_{z,d}T_{z,\theta}T_{x,a}T_{x,\alpha} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_j \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\theta_j & -\operatorname{sen}\theta_j & 0 & 0 \\ \operatorname{sen}\theta_j & \cos\theta_j & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & a_j \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_j & -\operatorname{sen}\alpha_j & 0 \\ 0 & \operatorname{sen}\alpha_j & \cos\alpha_j & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\theta_j & -\cos\alpha_j \operatorname{sen}\theta_j & \operatorname{sen}\alpha_j \operatorname{sen}\theta_j & a_j\cos\theta_j \\ \operatorname{sen}\theta_j & \cos\alpha_j\cos\theta_j & -\operatorname{sen}\alpha_j\cos\theta_j & a_j\operatorname{sen}\theta_j \\ 0 & \operatorname{sen}\alpha_j & \cos\alpha_j & d_j \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10} $$

Therefore, the transformation matrix between the reference frame 3 (reflector) and the origin of LT will be defined by equation 11:

$$ {}^{0}T_3 = {}^{0}A_1\ {}^{1}A_2\ {}^{2}A_3 \tag{11} $$

In this case, the value of each of these matrices will be as shown on equations 12-14:

$$ {}^{0}A_1 = \begin{bmatrix} \cos(\theta-90) & 0 & -\operatorname{sen}(\theta-90) & 0 \\ \operatorname{sen}(\theta-90) & 0 & \cos(\theta-90) & 0 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12} $$

$$^{1}A_{2} = \begin{bmatrix} \cos(\varphi-90) & 0 & \text{sen}(\varphi-90) & 0 \\ \text{sen}(\varphi-90) & 0 & -\cos(\varphi-90) & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

$$^{2}A_{3} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14}$$

Thus we can obtain the nominal position of the reflector with respect to LT origin in terms of R (d), H (θ) and V (φ).

5.1 Beam Offset (x_1)

The first error considered is the Beam Offset. In Figure 3 we can see that this error is equivalent to a change of position reference frame 0, equivalent to a displacement of nominal point "O" to point "A".

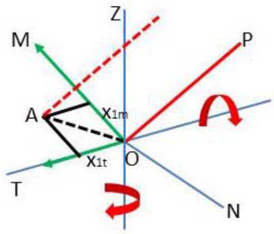

Fig. 3. Beam Offset.

The transformation matrix corresponds to a movement whose components are expressed in terms of its components on the axes M and T, so it becomes necessary to find its equivalence in the XYZ reference system generally based on the values of the tilt angles and azimuth being the same in the following manner:

$$Ex_1 = {}^{0}E_A = \begin{bmatrix} 1 & 0 & 0 & x_{1t}\cdot\cos(-\theta) + x_{1m}\cdot\sin(-\theta)\cdot\cos(-\varphi) \\ 0 & 1 & 0 & x_{1t}\cdot\sin(-\theta) - x_{1m}\cdot\cos(-\theta)\cdot\cos(-\varphi) \\ 0 & 0 & 1 & x_{1m}\cdot\sin(-\varphi) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{15}$$

5.2 Transit Offset (x_2)

Transit Offset is also a displacement of the initial reference system according to the model shown in figure 4.

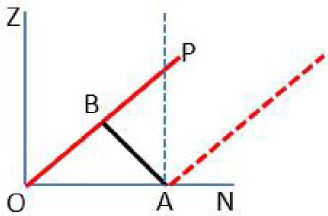

Fig. 4. Transit Offset.

In the same way as with the previous error we can obtain a transformation matrix between O and A:

$$Ex_2 = {}^{0}E_A = \begin{bmatrix} 1 & 0 & 0 & x_2 \cdot \sin(\theta) \\ 0 & 1 & 0 & x_2 \cdot \cos(\theta) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (16)$$

6. Synthetic generator of points mesh

Following the same process of obtaining frame exchange matrix for each of the errors, we obtain the general matrix coordinate transformation to the origin of LT reflector according to all geometric errors of the LT. This matrix is the product of the matrices obtained in the nominal model, with interleaved error in the same order of the laser beam path. In this way we are following the actual path of the laser beam including the geometric errors associated with the model.

Considering a set of giving values to the errors and defining a matrix of values for the parameters θ, φ and d, we can generate synthetic mesh of points with known errors, and then compare them with the nominal values. This will greatly help us because we want to establish a methodology which allows us to obtain the global error measuring different mesh of reflectors.

7. Influence of reflector errors

Measurement errors in LT systems are not only caused by the LT, the rest of the system components also take influence in the global error. In this case we will study the influence of the reflectors on the measurement uncertainty. Two types of reflectors will be tested, conventional SMR reflectors, in which the error depends on the angle of incidence of the beam on the reflector similar to experiments of Takatsuji et al. (1999) on the cat-eye's and reflectors with automatic tracking system (Active Target).

7.1 SMR tests

A test to determine the influence of the angle of incidence of LT on a SMR must have two elements: a centering system and a precise rotary measuring element. For positioning the SMR, a roundness table has been used to place the reflector with its magnetic base so it can rotate in a completely concentric. The measurement is performed with an interferometer that detects variations in reflector position when rotated. Figure 5 shows the mounting arrangement.

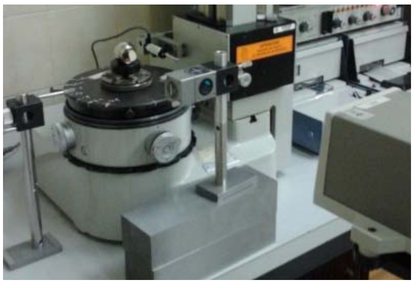

Fig. 5. Roundness table SMR test.

It is possible to turn the table into a range of ± 30° both horizontally and vertically without losing sight between the interferometer and the SMR. We consider an initial position corresponding to 0° tilt and 0° in azimuth and from this point the reflector is rotated in increments of 7.5° on each axis measuring the difference with the initial point. The results can be seen in Table 2.

Table 2. Optical errors of the SMR (μm)

		θ (°)								
		-30	**-22,5**	**-15**	**-7,5**	**0**	**7,5**	**15**	**22,5**	**30**
φ(°)	**-30**	13,4	13	12,4	11,5	10	8,3	6,5	4,3	2,6
	-22,5	8,1	7,9	7,6	6,9	6,2	4,3	3,2	1,6	0
	-15	5	4,8	4,5	3,8	3	2,1	0,8	-0,5	-1,6
	-7,5	2,4	2,2	2	1,5	0,9	-0,2	-1,1	-1,8	-2,8
	0	1,2	1	0,8	0,4	0	-0,7	-1,5	-2,4	-3,4
	7,5	0	-0,2	-0,4	-0,8	-1,3	-2	-2,6	-3,3	-4,1
	15	0,8	0,6	0,4	0	-0,5	-1,1	-1,8	-2,6	-3,2
	22,5			-0,5	-0,8	-1,3	-2	-2,7		
	30			-1,2	-1	-1,6	-2,4	-3,1		

7.1 Active target tests

The Active Target reflector has as a fundamental characteristic, it is capable of aligning with the laser emitter, whereby the angle of incidence of the beam is always optimal. To achieve this alignment, the Active Target is mounted on a gimbal mechanism with two degrees of freedom similar to the head of LT. Here lies the source of errors in the rotation axis. To see the influence of these factors tests have been developed to measure changes in position of the reflector at its rotation. The rotation about the vertical axis is simple, just focus the spotlight on the table of roundness and align with an interferometer. Rotating the roundness table, the variation on the interferometer measurement corresponds to the axis eccentricity. The rotation of the horizontal shows more problems and a 45º support has been proposed so it will produce the simultaneous rotation of the two axes as shown in Figure 6. Previously knowing the vertical axis error, the corresponding to the horizontal axis can be calculated.

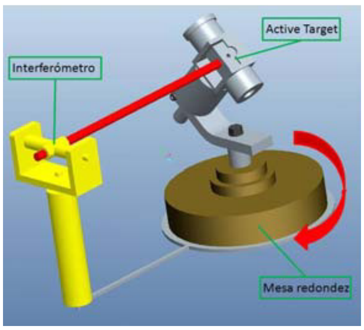

Fig. 6. Experimental setup for Active Target tets.

8. Conclusions

It has been shown the beginning of a process which will lead to with the development of a simple procedure for the calibration of laser tracker systems. The work done so far include the tests on SMR and planning of them with Active Target. Also the definition of LT models to study and geometric errors is at an advanced stage along with the definition of an automatic generator of synthetic data with simulated errors.

The work still to be done has different parts, first to analyze the test results and finish SMR and Active Target tests. It will also be necessary to complete the program to generate synthetic data and calculate the errors. Once the method to calculate LT errors will be finished, it will be validated with real data. Real data will be obtained from experimental tests measuring meshes of reflectors. It is expected that the geometrical errors won't be constant and will have some kind of dependence on the LT orientation, so it will be necessary to find its relationship with to the values of θ, φ and d. In this way we will have a global error correction based on LT reflector position, which should give a better correction that the simple calculation of geometric errors.

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