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Laser tracker kinematic error model formulation and subsequent verification under real working conditions

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Abstract

A kinematic model of the Laser Tracker (LT) based on the Denavit-Hartenberg method has been developed. In this model, error matrices have been included with error parameters for linear and rotary joints. The calibration method is based on the measurement of a mesh of reflectors measured by a LT from different positions. Error parameters are calculated knowing that distances between every pair of reflectors is the same regardless the LT position. The absence of nominal data prevents us from knowing the calibration behaviour and its suitability. Although synthetic data tests show a good accuracy improvement, it is not possible to know if this will work with under real working conditions. An experiment has been made to check the calibration procedure. A set of 17 reflectors have been placed on a Coordinate Measuring Machine (CMM) and have been measured by a LT from 5 different positions. Reflector positions have also been measured with the CMM to calculate the initial errors. With LT measurements we calculate the error parameters. LT measurements are recalculated considering the kinematic error model and compared with the CMM measurements to get the residual error. Two errors have been calculated; distances error between reflectors and their position error compared with CMM data.

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Keywords: *Laser tracker; kinematic model; calibration; accuracy; error model.*

1. Introduction

There has been a rapid development in recent years of long-range dimensional metrology systems for the verification of large-scale pieces, such as those in the aeronautic, spatial or naval sectors. The interest in LTs has

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been increasing because of their advantages in terms of accuracy, portability, flexibility (wide range of angles and distances in measurement), high speed in data acquisition, reliability [1, 2], automatic target tracking and high sampling rate [3]. The reliability of the system strongly depends on its proper calibration. Some standards like the ASME B89.4.19 [4] and the VDI 2617-10 [5] describe different tests to calculate the geometric misalignments that cause systematic errors in LT measurements. However, these tests do not give information about the individual error sources, and only provide information related to the suitable or unsuitable LT performance with respect to these standards. Moreover, these tests take a lot of time and require very specialized equipment. To know the individual error sources, a calibration procedure should be performed.

This calibration procedure must be able to identify individual errors from an error model who describes the LT real behaviour. It can be done with a kinematic model of the LT. This model is then extended with an error model. Error model is based on the individual error for every component of the LT kinematic chain. This model has been validated using synthetic data. As these data have been generated according to our model, the error parameters calculated give a very good LT accuracy, so it is necessary to use real data to know the accuracy increment our calibration method can obtain. The calibration procedure consists of identifying the geometric parameters in order to improve the measurement model accuracy. This process can be carried out in four steps: determination of the kinematic model by means of non-linear equations, data acquisition, geometric parameter identification and model evaluation.

2. Methodology

A kinematic model of the LT based on the Denavit-Hartenberg method [6] has been developed, see Fig. 1.

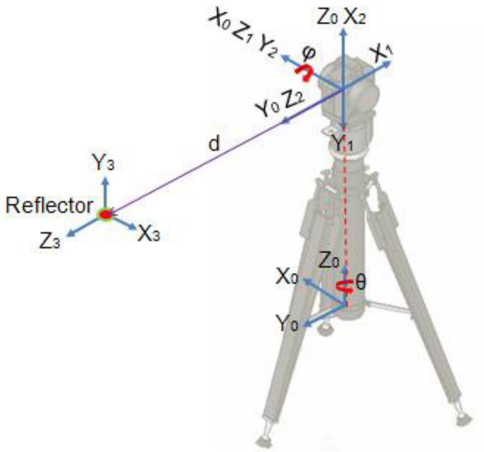

Fig. 1. Laser tracker kinematic model

The kinematic model establishes mathematical relations and obtains non-linear equations that relate the joint variables with the position and orientation of the end-effector [7]. This method has been widely used in mechanism modelling [8-10], and uses four parameters to model the coordinate transformation between successive reference systems. This method models the coordinate transformation between successive reference systems, using four parameters (distances di, ai, and angles θi, αi). The homogenous transformation matrix between frame i and i-1 depends on these four parameters as shown in equation 1.

$$ {}^{i-1}A_i = T_{z,d} \cdot R_{z,\theta} \cdot T_{x,a} \cdot R_{x,\alpha} = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \cdot \sin\theta_i & \sin\alpha_i \cdot \sin\theta_i & a_i \cdot \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cdot \cos\theta_i & -\sin\alpha_i \cdot \cos\theta_i & a_i \cdot \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Table 1 shows the values of the kinematic parameters corresponding to a LT with the beam source in the rotating head.

Table 1. D-H parameters.

i	d i (mm)	a i (mm)	θi (º)	αi (º)
1	0	0	θ-90	-90
2	0	0	φ-90	90
3	d	0	-90	0

In this model, error matrices have been included with error parameters for linear and rotary joints [11]. Errors are modelled by means of equation 2 for rotary and linear axis (see Fig. 2).

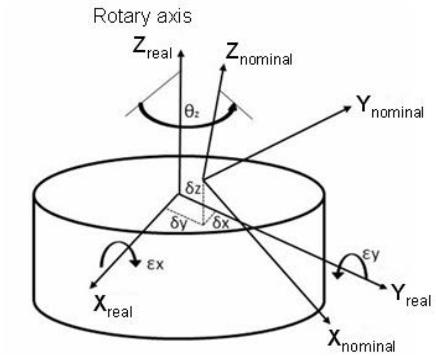

Fig. 2. Errors about an axis of rotation.

$$ R_{Terr} = \begin{bmatrix} \cos\varepsilon_Y \cdot \cos\theta_Z & -\cos\varepsilon_Y \cdot sin\theta_Z & sin\varepsilon_Y & \delta_X \\ \cos\varepsilon_X \cdot \sin\theta_Z + \sin\varepsilon_X \cdot sin\varepsilon_Y \cdot \cos\theta_Z & \cos\varepsilon_X \cdot \cos\theta_Z - \sin\varepsilon_X \cdot sin\varepsilon_Y \cdot sin\theta_Z & -\sin\varepsilon_X \cdot \cos\varepsilon_Y & \delta_Y \\ sin\varepsilon_X \cdot \sin\theta_Z - \cos\varepsilon_X \cdot sin\varepsilon_Y \cdot \cos\theta_Z & \sin\varepsilon_X \cdot \cos\theta_Z + \cos\varepsilon_X \cdot sin\varepsilon_Y \cdot sin\theta_Z & \cos\varepsilon_X \cdot \cos\varepsilon_Y & \delta_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

In the same way, linear axes present linear and angular errors identified with parameters δ_x, δ_y, δ_z, ε_x, ε_y and ε_z *as* shown on Fig. 3 and equation 3.

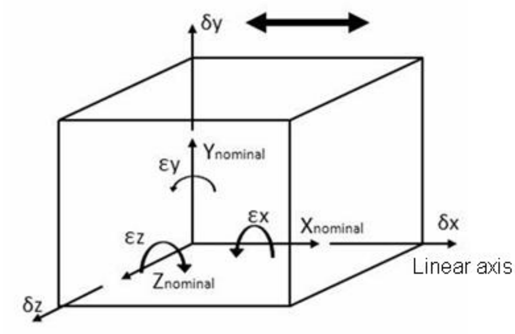

Fig. 3. Errors in a single axis linear motion.

$$T_{err} = \begin{bmatrix} 1 & -\varepsilon_Z & \varepsilon_Y & \delta_X \\ \varepsilon_Z & 1 & -\varepsilon_X & \delta_Y \\ -\varepsilon_Y & \varepsilon_X & 1 & \delta_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The system that provides the LT model considering the error matrices is calculated introducing error matrices. The result is given by equation 4:

$$^0T_3 = {}^0A_1 \cdot {}^0\mathrm{Re}\,rr_1 \cdot {}^1A_2 \cdot {}^1\mathrm{Re}\,rr_2 \cdot {}^2A_3 \cdot {}^2T\,\mathrm{e}\,rr_3 \quad (4)$$

This model presents 18 error parameters given by the vector $V\varepsilon$ (equation 5). This vector consists of the components *X*, *Y* and *Z* of the error parameters δ and ε for the azimuth angle, θ, elevation angle, φ, and distance, *d*.

$$V_\varepsilon = [\varepsilon_{X_\theta}, \varepsilon_{Y_\theta}, \varepsilon_{Z_\theta}, \delta_{X_\theta}, \delta_{Y_\theta}, \delta_{Z_\theta}, \varepsilon_{X_\varphi}, \varepsilon_{Y_\varphi}, \varepsilon_{Z_\varphi}, \delta_{X_\varphi}, \delta_{Y_\varphi}, \delta_{Z_\varphi}, \varepsilon_{X_d}, \varepsilon_{Y_d}, \varepsilon_{Z_d}, \delta_{X_d}, \delta_{Y_d}, \delta_{Z_d}] \quad (5)$$

The calibration method is based on the measurement of a mesh of reflectors measured by a LT from different positions. Error parameters are calculated knowing that distances between every pair of reflectors is the same regardless the LT position.

3. Experimental Procedure

Synthetic measurements have been generated to check the calibration method behaviour. Although synthetic data tests show a good accuracy improvement, it is not possible to know if this will work under real working conditions. An experiment has been made to check the calibration procedure. A set of 17 reflectors have been placed on a CMM and have been measured by a LT from 5 different positions. Reflector positions have also been measured with the CMM to calculate the initial errors, see Fig. 4.

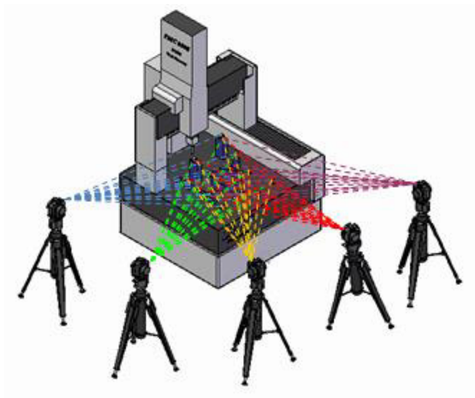

Fig. 4. Experimental setup.

The reflectors were measured with the CMM. These measurements are considered the nominal measurements in the data acquisition step. The LT then measured every reflector in every position, thus obtaining data measurements. The objective function minimizes the differences between all nominal distances given by every pair of reflectors (measured by the CMM), dCMMi, and the same distances measured by every LT, dmik.

The number of distances calculated for every position of the LT having 17 reflectors is 136. Thus, the number of distances to optimize for the 5 positions is 680 distances.

The objective function is given by equation 6.

$$\phi = \sum_{i=1}^{C_{n,r}} \sum_{k=1}^{LT} (d_{m_{ik}} - d_{CMM_{ik}}) \qquad (6)$$

where sub-index m is the measured distance obtained from the measurements of the LT, sub-index CMM is the measured distance obtained from the measurements of the CMM, sub-index i defines the distance to minimize, and k corresponds to the position of the LT.

The kinematic error parameter identification is usually carried out by means of approximation procedures based on least-squares fitting. The optimization technique used to solve the numerical optimization algorithm was the Levenberg-Marquart (L-M) [12] method, due to its proven efficiency in non-linear systems [13].

As the optimization and the validation criteria are the same, we need another validation criterion. Reflectors positions must be the same regardless the LT position so we can compare the reflector positions measured by the LT from different locations (instead of comparing distances) before and after calibration. In order to compare these LT measurements, all of them must be expressed in the same reference coordinate system. The LT measurements have been transformed from its own coordinate system to the coordinate system of the CMM. To do this, the transformation matrices between each LT reference system and the CMM reference system have been calculated. This process follows the methodology of absolute orientations to calculate the conversion frame matrix based on the use of quaternions [14]. The LT measurements can then be expressed in the CMM coordinate system.

The equation used to validate the calibration procedure for n reflectors and m LT locations is given by equation 7:

$$\phi = \sum_{i=1}^{m} \sum_{j=1}^{n} \sqrt{\left(x_j^i - x_j^{CMM}\right)^2 + \left(y_j^i - y_j^{CMM}\right) + \left(z_j^i - z_j^{CMM}\right)} \qquad (7)$$

Being x_j^i the *x* coordinate of reflector *j* measured form LT location *i* and x_j^{MMC} the *x* coordinate of reflector *j* measured by the CMM.

4. Results and Discussion

As it was mentioned in the data acquisition step, 17 reflectors were measured locating the LT in 5 positions. To perform the optimization, different strategies have been carried out:

a) The optimization is performed using the 17 reflectors and the 5 LTs.

b) The optimization is performed using 14 reflectors and the 5 LTs. 3 reflectors are kept as test data. Thus, the model will be validated in positions different from those used in the identification process.

c) The optimization is performed using 17 reflectors and 4 LT positions. 1 LT position is kept as verification data.

The results obtained in every strategy followed are presented below.

Fig. 5 illustrates the LT position error calculated as the difference between the error before the identification procedure, E_ini, and the error after performing the kinematic parameter identification for the three strategies a), b) and c). Strategy a) provides the error E_res. The error obtained is given by E_4LT when the positions measured by 4 LT are used in the identification procedure and 1 LT measurements are kept as test positions for the parameter evaluation procedure. Finally, E_14_ref corresponds to the error when the measurements of 14 reflectors are used in the identification procedure and the measurements of 3 reflectors are kept as test positions. 5 LT measurements are represented consecutively. The optimization that provides E_res was performed considering all measured points in the parameter identification. The points measured by L1 were kept as test positions in the parameter identification that gives E_4LT. Finally, the first thirty-five positions of each LT were kept as test positions in the parameter identification that provides E_14_ref.

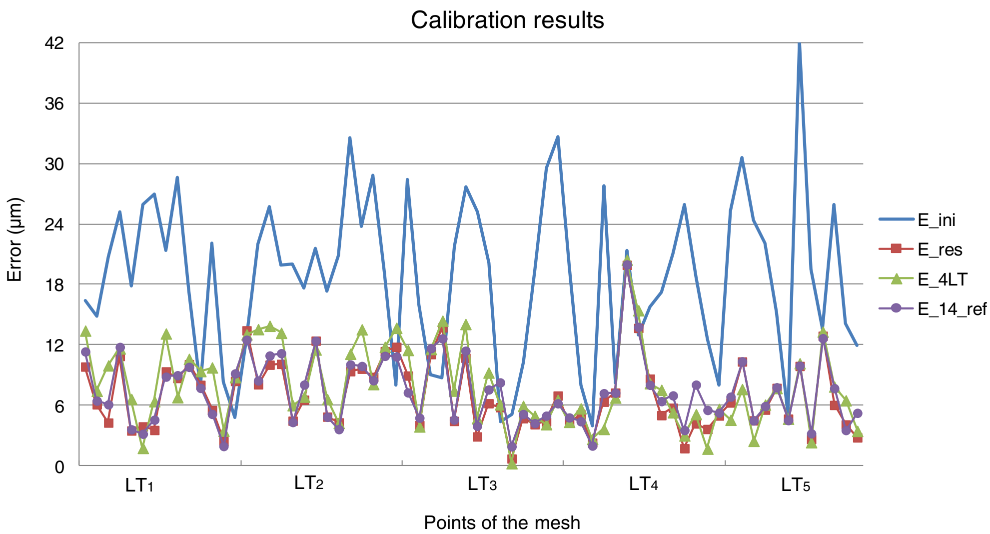

Fig. 5. Calibration results

Table 2 shows the maximum and mean errors obtained considering all points, the calibration points and the test points for every strategy.

The correction performed by means of the identification procedure decreases errors about a 62.50% using the strategy a), about a 57.47% using the strategy b) and 60.44% using the strategy c) with respect to initial errors. As it was expected, strategy a) presents the lower errors because all data have been included into the optimization. The difference between strategy a) and strategies b) and c) has a mean value of 1.54 µm and 0.74 µm for strategies b) and c), respectively, and a maximum value of 5.67 µm and 3.85 µm for strategies b) and c), respectively. These results verify that the identification procedure developed can be extrapolated to different positions within the LT workspace from those used in the identification procedure. Moreover, calibration results improve when some reflectors are kept as test positions with respect to decrease LT positions.

Table 2. LT initial errors and LT errors for every strategy.

	E_ini (μm)	E_res (μm)	E_4LT (μm)			E 14 ref (μm)		
			All points	Calibration points	Test points	All points	Calibration points	Test points
Maximum	42.06	19.935	20.45	20.45	14.39	19.98	19.98	11.34
Mean	18.78	7.045	7.99	7.39	9.97	7.43	7.49	7.15

5. Conclusions

A new kinematic model for a LT having the beam source in the rotating head has been developed. This model considers that errors depend on joints. The kinematic model behavior has been validated, generating synthetic measurements for a known nominal reflector coordinates and error parameters, thus, obtaining the values that would measure the LT if it had the prefixed errors. Measurements have then been corrected by identifying error parameters, thus, obtaining error parameters by means of the kinematic model. The comparison of the prefixed initial error parameters and the error values obtained allows us to validate the kinematic model developed.

All these verifications have been made for different meshes, obtaining that the spherical mesh is the one that allows us to analyse the correlation between parameters θ, φ and d and the errors more clearly.

An experimental calibration has then been performed, measuring the reflectors with both a CMM that provides nominal values and a LT located in different positions. To do this, different strategies have been followed, keeping different measurements as test positions. The parameter identification performed allows us to reduce the LT error about a 62%. Results show that the different strategies analyzed provide a calibration that can be extrapolated to different positions from those used in the identification procedure within the LT workspace. Moreover, calibration results improve when some reflectors are kept as test positions with respect to decrease LT positions.

6. Acknowledgements

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