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ORIGINAL RESEARCH PAPER

Error sources and models of the laser tracker without a beam steering mirror

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ABSTRACT

The laser tracker is a widely used instrument in many industrial and metrological applications with high demand measurement accuracy. Imperfections in construction and misalignment of individual parts deliver systematic errors in the measurement results. All error sources need to be identified and reduced to the minimum to achieve the best possible accuracy. The paper summarizes error sources of the laser tracker without beam steering mirror with emphasis on error modeling. Descriptions of error models are provided for the static and kinematic type of measurement.

KEYWORDS

systematic errors, corrections, accuracy, kinematic measurement, static measurement

1. INTRODUCTION

Any instrument used for measurement has imperfections that increase error in the measurement results. It is because parts of these measuring devices cannot be made and fitted together perfectly (ideally). In general, the accuracy of measurement is the closeness of the agreement between the result of a measurement and the measurand's true value [1]. One part of the measurement accuracy is delivered by the accuracy of the instrument itself. It is required that the instrument error's impact is minimal to achieve the measurement's best result. One of the possible approaches to deal with this problem is correctly identifying the device's error sources and reducing their impact on measurement results (mathematically or by measurement process).

The Laser Tracker (LT) is a measuring device. LT is a coordinate measuring system widely used in industry and metrology applications to provide high accuracy determination of the 3D position of measured points (on the level of several tenths of micrometers) [2–4]. Measuring tasks in industry and metrology often require the best possible accuracy. Therefore, identifying all error sources and reducing their influence on measurement results to a minimum is essential. These errors are caused by instrument imperfections (offsets, tilts, etc.), instability of the environment (change in atmospheric parameters which causes changes in the propagation of the light, refraction, etc.), or target properties (centering of the optics, pointing error, etc.). In this paper, LT error sources and their influence on the measurement are discussed.

The LT error sources depend on the design of the LT and the type of measurement. For better interpretation, a brief description of LT construction and components is provided. There are several construction types of LT; however, in this paper the focus is on the LT without a beam steering mirror. Error sources and error models during static measurement and kinematic measurement (when the target moves) are shown, and additional error parameters associated with LT are given in the end.

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2. FUNCTIONAL PRINCIPLES AND TYPES OF LASER TRACKERS

When addressing the issue of error sources and error modeling, construction of LT is essential. From the invention of LT in the mid-1980s, several changes appeared in used design and technologies. First LTs had a laser source placed in the base, and the laser was aimed to target via beam steering mirror (Fig. 1, left). In the next years, two new designs were developed: the laser beam is transmitted to the measuring head using fiber optical cable (Fig. 1, middle), or the laser source is placed directly in the measuring head (Fig. 1, right). In both, the second and third mentioned designs, the beam steering mirror is no longer used.

Despite the different designs, the principle of measurement is still the same. LT is continuously following a cooperative target with a laser beam, while its location is determined in terms of distance and two angles [6]. These two angles are: the azimuth (oriented angle measured in the LT horizontal plane from oriented direction to target) and the zenith angle (oriented angle measured in the LT vertical plane containing standing axis and target – measured form standing axis). Together, measured values serve for calculation of coordinates (1) in the LT Cartesian coordinate system (Fig. 2):

$$\begin{aligned} X_P &= d\cdot\cos\alpha\cdot\sin\zeta, \\ Y_P &= d\cdot\sin\alpha\cdot\sin\zeta, \\ Z_P &= d\cdot\cos\zeta, \end{aligned} \qquad (1)$$

where d is the slope distance; α is the azimuth; ζ is the zenith angle; X_p, Y_p, Z_p are the Cartesian coordinates of the point P.

LT has two rotating axes – vertical/standing axis (rotating the instrument) and horizontal axis (rotating the telescope). In the ideal situation, these axes are perpendicular to each other and create the origin of the LT Cartesian coordinate system (Fig. 2). Horizontal angle reading is done by horizontal angle encoder, which is placed coaxially with the standing axis. Vertical angle reading is done by vertical angle encoder placed coaxially with the horizontal axis. These angle encoders are practically same as in the total stations, and work on the same principle.

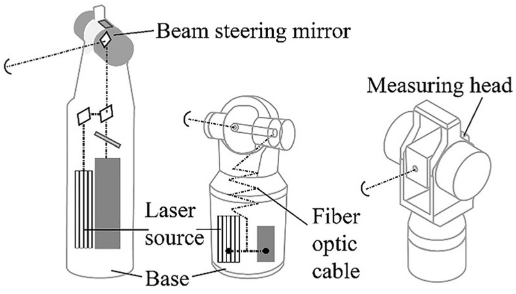

Fig. 1. Different LT design: with beam steering mirror (left); with fiber optic cable (middle); without beam steering mirror (right) (*Source:* Author(s) plot on the basis of [5])

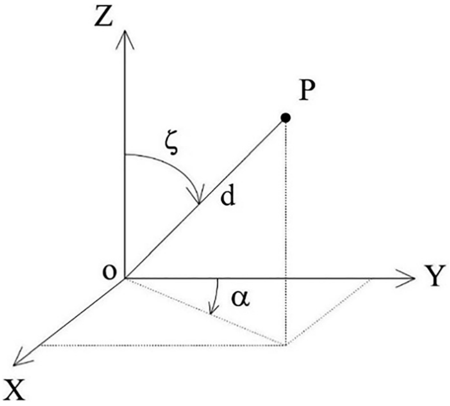

Fig. 2. Spatial polar method

The distance measurement is provided by three different technologies depending on the LT model. Laser interferometer was used in early versions of LT and is still used today [7]. The main advantages of this ranging technology are accuracy and speed of measurement. Unfortunately, the interferometer can determine only relative distances (difference to reference distance) and if the line of sight is broken during the measurement, the measurement has to start over (a new reference for interferometer is required). The second technology used is the so-called Absolute Distance Meter (ADM). ADM systems modulates [8] the laser beam, and applies phase measurement technique, to resolve the distance to the target. Typically, amplitude, frequency and angle of polarization of the laser beam are modulated. ADM can measure absolute distances (distance from geometrical centre of the LT to the target) but with slightly lower accuracy (several micrometers per meter) than interferometer. Also, the distance determination takes longer, so measuring a high-speed moving target can be challenging. On the other hand, a break in the line of sight is no longer a problem during measurement, which significantly improves LT usage. The last technology is called Absolute InterFerOMeter (AIFM), developed by Leica Geosystems [9]. It combines interferometer and ADM into one compact system, which overcomes the disadvantages of previously mentioned technologies. AIFM can perform high-speed absolute distance determination with the accuracy of the interferometric measurement.

The newest LT model from Leica geosystems, ATS600 [10] can provide distance measurement with or without the reflector. Reflectorless measurement is possible with enhanced wave form digitizer previously used by high-definition surveying tools. Therefore, Leica ATS600 can be used similarly to terrestrial laser scanners [11].

One of the primarily used functions that LT possesses is tracking cooperative target (retroreflector). For this purpose, a Position Sensing Detector (PSD) is used. When the LT is aimed at the target (reflector), part of the reflected laser beam is delivered to the PSD sensor. If the target is stationary, a zero point is defined on the sensor. After the target moves in any but the radial direction, the reflected laser

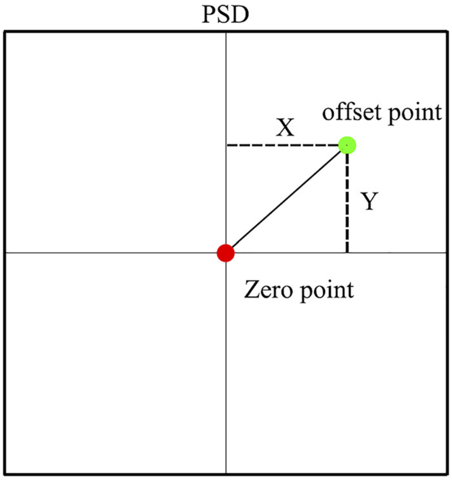

Fig. 3. Functional principle of the PSD sensor

beams on the PSD sensor moves as well, creating an offset of some value (Fig. 3). The offset can be decomposed on *X* and *Y* coordinates in the PSD coordinate system. Values *X* and *Y* are then used to calculate corrections for angles (horizontal and vertical) and to rotate LT back to the center of the reflector via the motorization system (reduce offset to zero).

The accuracy of the LT is changing depending on the individual model of the LT. Brief accuracy comparison of the selected LTs is shown in Table 1. All values are presented for static measurement only. The accuracy while performing kinematic measurement is described by manufacturers as to be 2–4 times higher.

3. ERROR SOURCES AND ERROR MODELS

Measurement results are practically always influenced by systematic and random errors. Random errors arise from stochastic temporal and spatial variations of influence quantities. It is not possible to compensate for the random error of measurement results; it can only be reduced by increasing the number of observations [1].

Systematic errors are caused by interfering factors (error sources) that appear during the measurement and, in a non-random way, affects measurement results. Systematic errors cannot be reduced by repeating the measurements, but by suitable measurement arrangement, mathematical corrections, calculations, etc. To achieve the best results of the measurements, the error sources need to be correctly identified, and their impact must be reduced.

In the case of the LT, systematic errors are often referred to as geometrical errors. Most of the error sources origins in geometrical and optical misalignments of the device. These misalignments introduce systematic errors in the measured distance and angles. A frequently used method to eliminate systematic errors is to include systematic effects as unknown parameters (creating an error model). The corrected (sometimes called true) quantities (distance and angles) are a function of measured values and several misalignments parameters. The corrections (2) can be expressed as [12]:

$$\begin{aligned} d_c - d_m &= \Delta d_m = f_d(d_m, \alpha_m,\ \zeta_m, x_1, x_2, \cdots, x_n), \\ \alpha_c - \alpha_m &= \Delta \alpha_m = f_\alpha(d_m, \alpha_m,\ \zeta_m, x_1, x_2, \cdots, x_n), \\ \zeta_c - \zeta_m &= \Delta \zeta_m = f_\zeta(d_m, \alpha_m,\ \zeta_m, x_1, x_2, \cdots, x_n,), \end{aligned} \tag{2}$$

where d_c, α_c, ζ_c are the corrected values; d_m, α_m, ζ_m are the measured values; Δd_m, $\Delta\alpha_m$, $\Delta\zeta_m$ are the corrections; x_i ($i = 1, 2, \ldots, n$) are the misalignment parameters. In general, Eq. (2) constitutes the LT error model. LT error model changes depending on individual LT design, construction and type of measurement. As was already mentioned, the LT without beam steering mirror is considered as it is mostly used nowadays. In the next part, the LT error sources and models for static measurement are described. Consequently, LT kinematic error sources and models are shown. In the last section, additional error sources affecting the measurements are briefly described to sufficiently cover the topic.

3.1. The LT error models for static measurement

When addressing the issue of the static error models for LT, the description of error sources needs to be made first. As was already mentioned, geometrical and optical misalignments are the main contributors to systematic errors. These misalignments arise because of the imperfection of individual parts, and their fitting together cannot be made perfect. There are many similarities between construction of LT and robotic total stations/theodolites which can be used in the LT error specification. More about theodolite and total station error sources and error modeling can be found in [13] or [14]. As it is shown in Fig. 4, the standing and horizontal (transit) axis in LT are not strictly perpendicular to each other and do not intersect. The laser beam should be perpendicular to the horizontal axis and emitting from the origin (intersection of standing and horizontal axis). Horizontal (azimuth) and vertical (elevation) angle encoders should be placed coaxially with the standing axis and horizontal axis, respectively.

From these geometrical error sources, a set of misalignment parameters for the error model can be specified. Muralikrishnan et al. [12] published an error

Table 1. Accuracy comparison of the selected LTs [2–4]

Parameters	Leica AT 960	Faro Vantage	API Radian
Angle accuracy	±15 µm + 6 µm/m	±20 µm + 5 µm/m	±10 µm or 5 µm/m
Distance accuracy	±10 µm + 0.5 µm/m	±16 µm + 0.8 µm/m	±15 µm or 0.7 µm/m*
Level accuracy	±1.0 arc sec	±2.0 arc sec	±2.0 arc sec

*Whichever is greater.

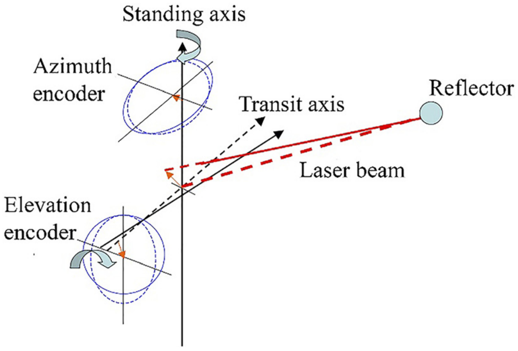

Fig. 4. LT geometrical errors
(*Source:* Author(s) plot on the basis of [15])

model for LT without beam steering mirror containing 15 parameters. This model is an adaptation of the older model from Loser and Kyle [16] for LT without beam steering mirror and is applicable only for front face measurement. Description of parameters is shown in Table 2, and more details can be found in [12]. The error model can be written as follows (3):

$$\begin{aligned} d_c &= d_m + x_2 \cdot \sin\zeta_m + x_8, \\ \alpha_c &= \alpha_m + \frac{x_{1t}}{d_m \cdot \sin\zeta_m} + \frac{x_{4t}}{\sin\zeta_m} + \frac{x_5}{\tan\zeta_m} + x_{6x} \cdot \cos\alpha_m - x_{6y} \cdot \sin\alpha_m + \\ &\quad + x_{9a} \cdot \sin(2\alpha_m) + x_{9b} \cdot \cos(2\alpha_m), \\ \zeta_c &= \zeta_m + \frac{x_{1m}}{d_m} + \frac{x_2 \cdot \cos\zeta_m}{d_m} + x_3 + x_{7n} \cdot \cos\zeta_m - x_{7z} \cdot \sin\zeta_m + \\ &\quad + x_{10a} \cdot \sin(2\zeta_m) + x_{10b} \cdot \cos(2\zeta_m). \end{aligned} \tag{3}$$

Another error model was introduced by Hughs et al. [15], which modified Muralikrishnan's model. The new model delivered three changes:

1. vertical angle zero position was placed in horizontal plane;
2. model was extended to include back face measurement;
3. scale error on the range was introduced.

The stochastic model was derived from the modified deterministic model by adding noise terms on all measured values. Numerical evaluation of errors was performed by network measurement and can be found in [15].

Table 2. Error parameters for LT without beam steering mirror

x_{1t}, x_{1m}	Beam offset
x_2	Transit offset
x_3	Vertical index offset
x_{4t}	Beam tilt
x_5	Transit tilt
x_{6x}, x_{6y}	Horizontal angle encoder error
x_{7n}, x_{7z}	Vertical angle encoder error
x_8	Bird-bath error*
x_{9a}, x_{9b}, x_{10a}, x_{10b}	Second order scale errors in the encoders

*Applicable for LT with interferometer only.

Conte et al. [17] proposed a kinematic error model for LT using Denavit-Hartenberg notation. In this case, the word "kinematic" can lead to confusion because it is not connected with a spatiotemporal measurement of the moving target. The error model is developed by the coordinate transformation between successive reference systems of LT and contains 18 error parameters. The model was validated using synthetic data, and obtained error parameters can be found in [17].

Mentioned error models can be used to evaluate systematic errors for LT without beam steering mirror when measuring on static target. Basic concepts about error modeling for kinematic measurement are described in the next section.

3.2. The LT error models for kinematic measurement

Kinematic error models can be based on static error models (3). It is because every systematic error, which appears during the static measurement is present during kinematic measurement as well. However, new error sources needs to be considered when measuring a moving target. It is assumed that kinematic error parameters have a smaller value than static error parameters when the target speed and acceleration are relatively slow [18]. Research of individual systematic errors during the kinematic measurement is explored to some extent, but a detailed description of kinematic error models is not commonly provided.

As was mentioned in section 2, the PSD sensor is used to track the moving target, and readings from the PSD sensor are used to correct angle measurement. Therefore, any systematic effects that originate from PSD sensor readings can affect the measurement result. Loser and Kyle [16] wrote an error model for LT with beam steering mirror introducing correction for angles, which can be used in this situation. The correction for horizontal angle (4) can be written as follows:

$$x_{PSD\alpha} = \frac{H_{off}}{d_m \cdot \sin\zeta_m} \tag{4}$$

and for vertical angle (5):

$$x_{PSD\zeta} = \frac{V_{off}}{d_m}, \tag{5}$$

where: H_{off}, V_{off} are additional terms that come from the internally corrected PSD readings. Eqs (4) and (5) can be added as new parameters to Eq. (3) for angles and provide further corrections.

Another systematic error is delivered by synchronization of individual measurements provided by LT (angles, distance, PSD readings, etc.). When measuring on a static target, little delays between measurements are not an issue because the target is not changing position. However, during kinematic measurement, any delay causes that individual measurements are made for a different points in space, introducing systematic error in the measurement result. This systematic error depends on the speed and acceleration of the target. Higher speed and acceleration deliver higher systematic errors. Ulrich [5] provided equations for kinematic 3D point determination if one delay time includes the delay time for distance and angles. Time delay between azimuth and zenith angle can be neglected. Using (1), (3), (4), and (5) with the addition of time synchronization parameters, the corrected 3D point coordinates are given as (6):

$$\begin{aligned} X_c &= d_c \cdot \cos\,\alpha_c \cdot \sin\,\zeta_c + v_x \cdot t_s + \frac{1}{2} a_x \cdot t_s^2, \\ Y_c &= d_c \cdot \sin\,\alpha_c \cdot \sin\,\zeta_c + v_y \cdot t_s + \frac{1}{2} a_y \cdot t_s^2, \\ Z_c &= d_c \cdot \cos\,\zeta_c + v_z \cdot t_s + \frac{1}{2} a_z \cdot t_s^2, \end{aligned} \tag{6}$$

where v_x, v_y, v_z are the speed components for each axis; a_x, a_y, a_z are the acceleration components for each axis; and t_s is the time synchronization error.

As the next error, source interpolation of the measured values can be considered. Present LTs have a higher measurement rate (for example, 3 kHz) than the output rate (1 kHz). The slower output rate is caused by hardware limitations (Local Area Network (LAN), Computer Performance (PC), client program design). Interpolation of measured values has to be made to satisfy slower output. Each measurement is provided with a timestamp (with 1 μs resolution) from an internal clock of the LT controller. This timestamp is used to correctly interpolate measurement values. The interpolation process can deliver significant systematic errors to the measurement result if the target is moving with high speed and/or high acceleration. However, incorporating the interpolation error parameter to the kinematic error model is a very complex problem, probably impossible to solve.

3.3. Additional error sources

In this section, a brief description of additional error sources and systematic errors is given. They are not included in the above-mentioned error model, because they can be reduced by measurement procedure or systematic corrections.

Part of the LT measuring system is a cooperative target (for example, a spherically mounted reflector), which cannot be manufactured perfectly. The measurement result is therefore affected by the quality of the reflector geometry. In general, the reflectors used with LTs are very accurate in the sense of centering the optics (with tolerances better than ±3 μm) and roundness (with tolerances better than ±3 μm). More detailed information about reflector errors can be found in [9, 19].

Very important elements while performing measurement are environmental conditions. The accuracy of the measured distance is significantly dependent on the accuracy of the determination of temperature, relative humidity, and air pressure. These environmental parameters are measured by sensors incorporated into LT, and corrections are applied automatically. Environmental sensor must be regularly calibrated to deliver the correct readings.

Another systematic effect is a phenomenon called the warm-up effect. After the LT is turned on, the laser source is raising its temperature so it can be used for measurement. During this process, the other parts of the LT are heating up as well. Due to the thermal expansion of the components inside the LT, various shifts and misalignments occur. To reduce the warm-up effect, the measurement should be performed after the temperature inside the device has been stabilized. The time interval after which the temperature stabilizes is called the warm-up time and generally could be given by [20].

Present LTs have an integrated inclination sensor, measuring the deviation between the vertical axis of the LT and the plumb line (gravity vector). Measured values are then automatically corrected of this deviation. Inclination sensor is providing measurements on some level of accuracy (Table 1) and adding systematic error to the measurement results.

4. CONCLUSIONS

This paper is providing a summarization of the error sources and error models of the LT without beam steering mirror. Static error models (also referred to as geometrical models) were evolving during the time and are well described. Systematic errors arise from multiple geometrical and optical misalignments of the LT. Kinematic error models are based on static error models with additional parameters. However, they are still in the phase of development. Several approaches to this problem are given in this paper, with adequate explanations.

The main contributors to LT measurement uncertainty are geometric and optical errors (i.e., axis tilts, offsets, etc.). It is hard to provide the specific values as they depend on individual LT and can change over time. For example, the LT API's geometric error values (model T3) can be found in [21]. Kinematic measurements are introducing additional errors (i.e., time synchronization error). The impact of kinematic errors on measurement is negligible if the target moves slowly and increases with higher speed. However, kinematic errors are considered less significant in comparison with geometric errors. Error sources originating from LT equipment (i.e., reflectors, mounts) affect measurement uncertainty in the order of several micrometers. Environment instability may affect the measurement accuracy in several ways. Changes in atmospheric parameters affect distances (changes in the propagation of the light) and angles (refraction). Vibrations can be present in the shop floor environment and make the measurement almost impossible. Reduced impact of environmental errors still may contribute to measurement uncertainty in the level of micrometers or tenths of micrometers.

During LT measurement, several things have to be considered to reduce the impact of error sources and achieve declared LT accuracy. The LT should be regularly tested and calibrated in intervals specified by the manufacturer. Quick geometrical parameters check should be done after transportation of the LT and is also recommended before each measurement. Measurement and manipulation with LT should be done according to the user manual to avoid any unusual measurement results. The environment should be as stable as possible and atmospheric parameters correctly measured to apply corrections.

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