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Methodology for the kinematic testing of the laser trackers

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Abstract

Title: Methodology for kinematic testing of the laser trackers

The thesis provides a comprehensive summary of the theory about kinematic error sources, influencing factors, and kinematic testing of the laser trackers. The theory is followed by the practical part, which consists of three individual experiments focused on the laser tracker's kinematic performance. The first experiment is aimed to determine the time delay between polar measurements of the laser tracker. The second experiment is aimed at the uncertainty determination of the distances and angles during kinematic measurements. A portable shaker vibration calibrator was used in both experiments to create an oscillating movement of the target. The last experiment verified the new proposed laser tracker kinematic field testing methodology. For this purpose, a new piece of equipment (a rotating wheel with a mounting system) was invented, allowing a quick check of the laser tracker's kinematic performance.

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1. Introduction

Nowadays, measuring moving targets (for example, industrial robots) is becoming more common to automate the whole workflow in industrial applications. This process can be described as kinematic measurement and can be performed by the Laser Tracker (LT). However, with the kinematic measurement, it could be challenging to introduce all relevant influencing factors and adequately describe the uncertainty of measured quantities. Previous research mainly focused on influencing factors, error models, uncertainty evaluation, and testing procedures for static measurement only. However, there is still no comprehensive procedure or standard addressing the kinematic testing issue. By systematically evaluating the kinematic performance of the LT, manufacturers, and users can ensure that the instrument consistently delivers reliable and accurate measurements. This is critical for maintaining the quality of manufactured products, validating components in engineering processes, and meeting stringent industry standards.

2. Goals of the thesis

The goals of the thesis could be summarized into the following points:

- Analysis of the current state of the art regarding the LT error sources and kinematic testing.
- Development of the kinematic error model and design of experiment for determination of kinematic uncertainty of LT.

- Performance of an experiment for the LT kinematic uncertainty determination.
- Development of the methodology for the kinematic field testing.
- Verification of the kinematic testing procedure by experimental measurement.
- Creation of an application for the LT control and testing automatization.

3. State of the art in the field of research

The LT (Fig.1) is a polar coordinate measuring system in which a cooperative target is continuously followed with a laser beam, and its location is determined in terms of distance and two angles (STN EN ISO 10360-10, 2016). Position determination is based on a well-known spatial polar method frequently used in geodesy.

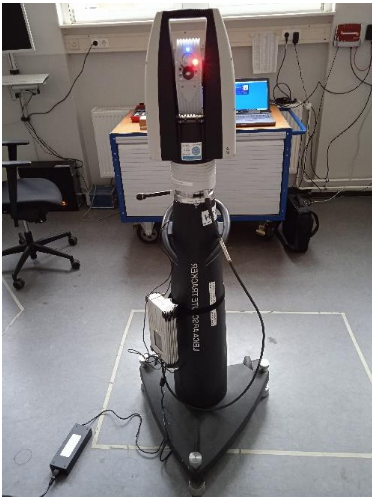

Fig. 3.1 – Laser Tracker Leica AT960-LR

Many influencing factors come from the imperfect manufacturing of individual components of the LT and their assembly. This large group of factors is often called geometric errors. Apart from geometric errors, many error sources depend on external environment conditions, observer experience, type of sensors used, type of measurement, and many others.

Since the general design of the LT is very similar to the total stations and theodolites, much useful information can be drawn from the existing literature (Deumlich, 1982; Kunkel, 2012). Description of LT geometric errors for the LT with beam steering mirror provided (Loser & Kyle, 1998). Further expansion of geometric errors for the LT without a beam steering mirror was described by (Muralikrishnan, 2009; Hughes et al., 2010).

Correct measurement procedures can reduce the systematic effect of some geometric errors. For example, two-face measurements are commonly used to eliminate collimation errors. Another way to reduce systematic error is to mathematically calculate their value and correct the measured quantities (distances and angles). The error model describes the functional dependency between measured values and several misalignment parameters, which are included as unknown parameters. The corrections (3.1) can be expressed as (Muralikrishnan, 2011):

$$\begin{aligned} d_c - d_m &= \Delta d_m = f_d(d_m, \alpha_m,\ z_m, x_1, x_2, \cdots, x_n), \\ \alpha_c - \alpha_m &= \Delta \alpha_m = f_\alpha(d_m, \alpha_m,\ z_m, x_1, x_2, \cdots, x_n), \\ z_c - z_m &= \Delta z_m = f_z(d_m, \alpha_m,\ z_m, x_1, x_2, \cdots, x_n,), \end{aligned} \tag{3.1}$$

where:

d_c, α_c, z_c - corrected values,

d_m, α_m, z_m - measured values,
$\Delta d_m, \Delta\alpha_m, \Delta z_m$ - corrections,
$x_i (i = 1,2,\dots,n)$ - the misalignment parameters.

Muralikrishnan (Muralikrishnan, 2011) published an error model for LT without a beam steering mirror containing 15 parameters. It is an adaptation of the older model from Loser and Kyle (Loser, 1998) for LT without a beam steering mirror and is applicable for front face measurement only. Hughs et al. (Hughes, 2010) introduced another error model, which modified Muralikrishnan's model. 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 (Hughes, 2010). Conte et al. (Conte, 2016) proposed a kinematic error model for LT using Denavit-Hartenberg notation.

More LT error sources are hard to classify into specific groups. Some depend on the environmental conditions, some are delivered by the targets (reflectors), and some originate from other physical phenomena. Most of them apply to static and kinematic measurements, but there can be differences in how they affect the measurement result. The thesis provides an in-depth summary of the influencing factors present during kinematic measurement, which can serve as a comprehensive basis for further research.

3.1. LT testing procedures

Like any system used for measurement, the LT must undergo repeated testing and confirmation of whether it meets the accuracy declared by the manufacturer. Since the LT is often used in kinematic applications (e.g., industrial robot calibration), verifying the LT performance during kinematic measurement is crucial. Static testing procedures are described in detail in the three standards (ASME B89.4.19, 2006; VDI/VDE 2617-10, 2011; STN EN ISO 10360-10, 2016). The standards generally describe multiple static measurement tests for verifying LT performance by measuring calibrated lengths, spheres, and surfaces. The difference between the calibrated reference value and the measured value is compared with the MPE (Maximum Permissible Error). However, there is no standard addressing the issue of kinematic testing yet.

Ulrich provided extended work on kinematic uncertainty determination and summarized his findings in his dissertation (Ulrich, 2016). Another research (Morse, 2015) shows a set of tests to characterize the performance of the three different LTs while collecting data from a moving target. Firstly, the target is moved by hand on the plane along the gauge block. Secondly, a circular motion test was performed by measuring a moving target on the rotating ballbar apparatus with a very stable motion. The uncertainty modeling using the PSVC (Portable Shaker Vibration Calibrator) was performed by Omidalizarandi (Omidalizarandi, 2020). A simple method for kinematic testing of the LT in the field was published by Parker (Parker, 2020), using a plane pendulum.

4. Methodology

Three separate experiments were conducted to achieve the goals stated in chapter 2. The first experiment was used to calculate the time delay between measured angles and distances. The time delay represents a significant error source specific to kinematic tasks. The second experiment was dedicated to the kinematic measurement uncertainty evaluation. The PSVC was used for both experiments to create target movement and served as a reference. The third experiment was used to verify the new proposed methodology for the kinematic field testing. In this case, new equipment was developed (wheel with mounting system) to quickly check the LT performance in the field.

4.1. Time delay evaluation

The main idea for the experiment is to measure the moving reflector attached to the PSVC (Fig. 4.1) with the LT. The PSVC is a device capable of generating low-frequency movements based on an internal high-resolution quartz reference accelerometer. Movement is performed only in one direction (vertical) with high accuracy.

Fig. 4.1 – PSVC 9210D

The harmonic oscillation in the PSVC has known predefined acceleration amplitudes and frequencies, which are very accurate and stable during the experiment. The movement of the reflector is then tracked and observed by the LT. As the PSVC can create only vertical movement, we looked for changes in the measured vertical angle and distance. The peaks should occur simultaneously in the distance and angle measurements without delay. If there is a time delay between the angle and distance measurements, the peaks will be observed at different times (Fig. 4.2). The peak of time difference corresponds to the time delay. In addition, the assumption is made that the time delay between horizontal and vertical angle measurements can be neglected.

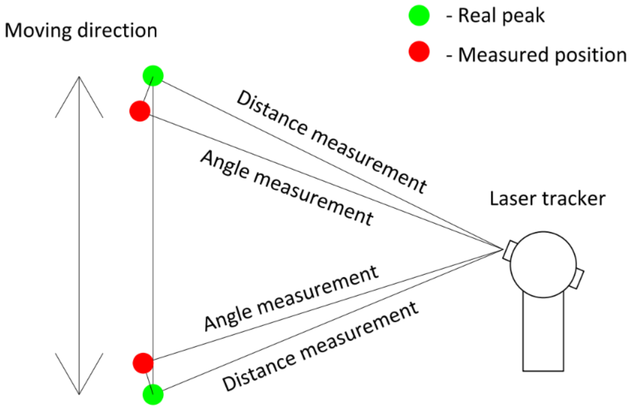

Fig. 4.2 – Measurement with the time delay between angles and distance measurements

4.2. Kinematic uncertainty modelling

The general idea is to create a stable movement with the PSVC, which can be measured with the LT. In the next step, the regression analysis for harmonic oscillation is used to fit the sine curve to the measurements. The standard deviation between fitted and measured data can be interpreted as the uncertainty of individually measured quantities.

For this idea to work, measured quantities must be considered separately so they do not interfere with others. However, the PSVC creates only vertical movement, so a different experiment configuration must be made to achieve this goal. When the LT is in the standard (vertical) position, and the PSVC is placed at the same height as the LT, the change can be seen in the measured vertical angle (changes in the distance and horizontal angle are heavily reduced). As the PSVC movement direction cannot be changed, we had to change the orientation of the LT. To analyze the horizontal angle, the LT has to be placed horizontally (Fig. 4.3 - left), and to analyze distance, the LT has to be placed upside-down (Fig. 4.3 - right). Construction of the LT allows different mounting options to achieve such a configuration.

Fig. 4.3 –LT horizontal mounting (left), upside-down LT mounting (right)

After obtaining the data, the next step was to best fit the sine curve to the data based on regression analysis. The regression equation for the sine curve (4.1) can be described as follows:

$$y = A \cdot sin(Bx + C) + D, \tag{4.1}$$

where: A – amplitude, $B = 2\pi f$, f – frequency, C – phase shift, D – offset.

The next step is to calculate the standard deviation of the difference between fitted and observed data based on equation (4.2):

$$\sigma_{diff} = \frac{1}{n-1}\sqrt{\sum_{i=1}^{n}\left(y_{diff_i} - \overline{y_{diff}}\right)^2}\ , \tag{4.2}$$

while:
$y_{diff} = y_{fitted} - y_{observed}.$

Standard deviation σ is interpreted as uncertainty for individually observed values (angles and distance) during kinematic measurements.

4.3. Methodology for kinematic field testing

Field testing aims to check the instrument performance on the shop floor and current environmental conditions. The stress during the operation and transportation of the LT may cause misalignments of internal parameters or other defects that are difficult to recognize. Field tests do not provide error parameters values but rather information about instrument measurement capability.

To perform a kinematic test, the reflector has to move alongside some regular and steady trajectory. This is because the trajectory has to be reliably approximated by a discrete set of static points. For this purpose, new equipment consisting of the rotating wheel and mounting system was developed (Fig. 4.4). The wheel from the bicycle with the removed axle and with a diameter of 57.3 cm is used. The centering of the wheel was professionally adjusted beforehand. A metal extension for the reflector holder is attached to the wheel rim.

Fig. 4.4 – Prototype of the kinematic field testing equipment on the tripod

After assembling the prototype on the tripod, a magnetic holder can be placed on the extension together with the reflector. The wheel can be rotated freely or can be precisely positioned and held in place by clamp screws. This allows both static and kinematic measurements to be made.

The general idea of the testing procedure is straightforward. At first, a static measurement is performed, which will serve as a reference for kinematic measurement. The wheel is rotated at a constant angle and held in place by a clamp screw. A set of points is observed that creates a circular trajectory of the wheel. Right after that, a kinematic measurement is performed with a freely rotating wheel. Subsequently, the circle regression for both static and kinematic measurements can be calculated and compared. Two main characteristics for comparison are the radiuses of the wheel and the standard deviation of distances from measured points to the fitted circle. A significant difference between these characteristics indicates a possible problem with the LT kinematic performance.

5. Results and discussion

This chapter summarizes the results of individual experiments together with a discussion. The chapter is divided in the same ways as the previous one to provide better clarity.

5.1. Time delay evaluation results

Based on the process described in chapter 4.1, the mean value and the standard deviation for different data sets (different frequency and acceleration amplitude) were calculated (Table 5.1). The mean value represents the time delay between the measured slope distance and vertical angle.

Table 5.1 – Example of the calculated time difference between a vertical angle and distance peaks

Distance from tracker	1.5 [m]			
Measurement rate	1000 [Hz]			
Reflector	0.5" RRR		1.5" RRR	
	Mean [s]	STD [s]	Mean [s]	STD [s]
1. set	-0.0002	0.0013	0.0004	0.0015
2. set	-0.0003	0.0005	-0.00002	0.0007
3. set	-0.0002	0.0005	-0.0003	0.0008
4. set	-0.0001	0.0004	0.0010	0.0006
5. set	-0.0002	0.0004	**0.0085**	0.0005
6. set	-0.0002	0.0004	**0.0079**	0.0003
7. set	-0.0002	0.0004	**0.0081**	0.0003

In most scenarios, the time delay (peak difference) is zero or very close to zero (difference of 1 ms). The exception from zero time delay occurs only when the 1.5" RRR is used, and the movement amplitude acceleration is from 10 to 12 m/s^2 with a frequency of 20 Hz.

5.2. Kinematic measurement uncertainty results

Differences between measured and fitted values were obtained according to the approach described in chapter 4.2. The standard deviation of these differences is interpreted as uncertainty characteristics for individual measured quantities (vertical and horizontal angles and distances). Fig. 5.1 and 5.2 show standard deviations for vertical and horizontal angles based on distance. Fig. 5.3 shows the standard deviation for the measured distance, and the red dashed line in the plots represents the LT static accuracy specified by the manufacturer.

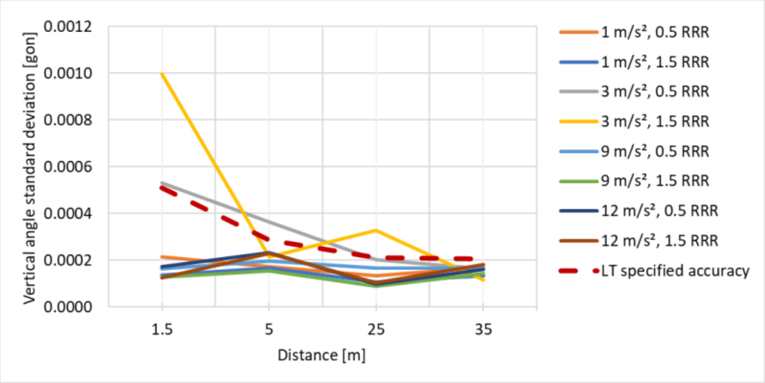

Fig. 5.1 – Comparison of the standard deviations for vertical angle measurements based on distance

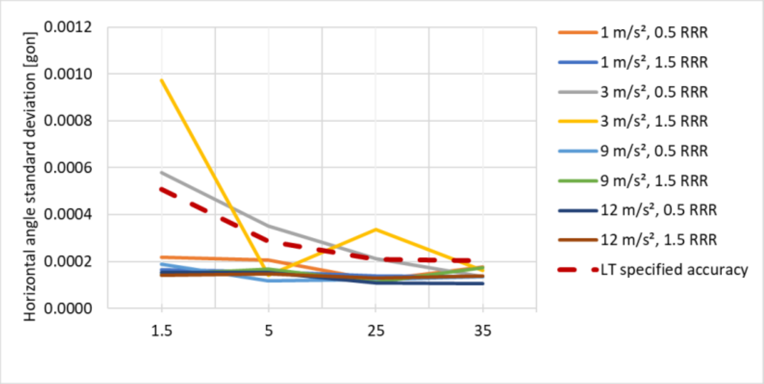

Fig. 5.2 – Comparison of the standard deviations for horizontal angle measurements based on distance

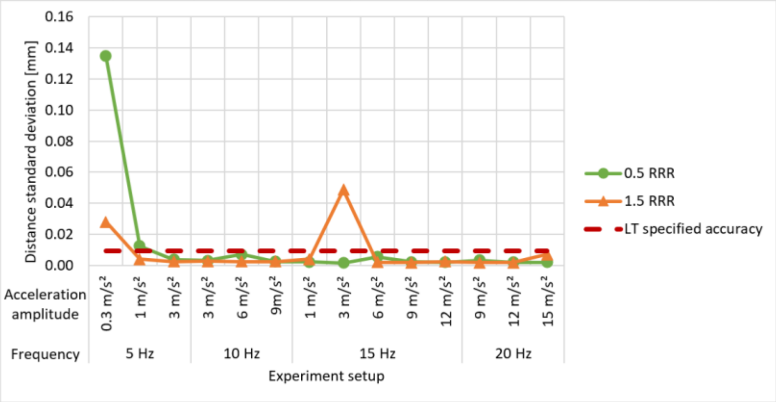

Fig. 5.3 – Standard deviations for distance measurements

In most cases, the calculated uncertainty/standard deviation is below the accuracy specified by the manufacturer, indicating very good kinematic performance. However, the configuration with a frequency of 5 Hz and amplitude of 3 m/s^2, exceeds the manufacturer's specification for both vertical and horizontal angle measurements (Figures 5.1-5.2). This indicates some systematic effect present in the data. The most probable cause is the instability of the PSVC movement in this particular movement configuration. Distance standard uncertainty is, in most cases, better or very close to the values specified by the manufacturer (Fig. 5.3). The exception is when the reflector movement was with small amplitude (0.3 m/s^2) and frequency (5 Hz), which was probably caused by the instability of PSVC vibration.

5.3. Kinematic field tests

The kinematic testing procedure was performed according to the methodology described in chapter 4.3, obtaining 32 datasets. Two main characteristics for the results analysis are the wheel's radius and the standard deviation of distances from measured points to the fitted circle.

Table 5.2 – Set 3 - results for kinematic measurement

Set 3 – slow movement	**Static**	**Clockwise 1**	**Clockwise 2**	**Counterclockwise 1**	**Counterclockwise 2**
Center point X [mm]	*-202.140*	-202.164	-202.150	-202.163	-202.173
Center point Y [mm]	*1149.247*	1149.189	1149.244	1149.203	1149.199
Center point Z [mm]	*25.528*	25.417	25.409	25.414	25.421
Radius [mm]	*286.502*	286.502	286.504	286.504	286.504
Standard deviation [mm]	*0.007*	0.019	0.017	0.018	0.020
Mean [mm]	*0.000*	0.000	0.000	0.000	0.000
Mean angular velocity [rad/s]	-	0.270	0.424	0.338	0.340

Set 3 – fast movement	**Static**	**Clockwise 1**	**Clockwise 2**	**Counterclockwise 1**	**Counterclockwise 2**
Center point X [mm]	*-202.140*	-202.167	-202.162	-202.180	-202.178
Center point Y [mm]	*1149.247*	1149.277	1149.246	1149.278	1149.268
Center point Z [mm]	*25.528*	25.415	25.403	25.416	25.428
Radius [mm]	*286.502*	286.503	286.498	286.502	286.497
Standard deviation [mm]	*0.007*	0.030	0.029	0.031	0.030
Mean [mm]	*0.000*	0.000	0.000	0.000	0.000
Mean angular velocity [rad/s]	-	0.494	0.456	0.486	0.486

The following points give summarization of the kinematic field testing procedure:

Preparation:

1. Acclimatization of the LT, initialization, and waiting for the temperature stabilization (reducing the warm-up effect) for at least 1 hour and 20 minutes.
2. Assemble and positioning of the testing prototype (at the closest distance from the LT and the same height).

Measurement:

3. Static measurement of the 10 points evenly distributed on the wheel.

   The wheel is rotated at a constant angle and held in place by a clamp screw to measure individual points. Standard mode with the 1,5" RRR is used.
4. Kinematic measurement of the rotating wheel.

   The rotation speed should be high enough to have at least three complete rotations of the wheel. At least two different measurements should be performed to calculate $\frac{\rho}{E}$ parameter (eq. 4.26). A recommendation is to perform clockwise and counterclockwise rotations.

Evaluation:

5. Evaluation of the static measurement.

   The best-fit of the circle from the measured points and obtaining the circle radius. Calculation of the distances from the circle center to the measured points. Eliminating the linear trend from the calculated distances. Calculation of the standard deviations of the distances with the removed linear trend.

6. Evaluation of the kinematic measurement.

   Adjustment of the observation (removal of the shaky data from the beginning of the measurement). Best-fit of the circle from kinematic measurement and obtaining the circle radius. Calculation of the angular velocities and radius correction. Calculation of the distances from the circle center to the measured points. Removal of the linear trend from the calculated distances. Calculation of the standard deviations of the distances.

Results analysis:

7. Comparison of the calculated radiuses and standard deviations against the threshold.

   A decision about the kinematic performance of the LT.

Performing the proposed testing methodology is very fast. The whole measurement process can be finished in under ten minutes (after the warm-up phase). Currently, the invented prototype has proved its usability for kinematic field testing. The prototype is easy to assemble, use, and transport and not complicated to manufacture. The overall cost is hard to estimate as the material used was from scraps, but an optimistic guess is around 300€ (material + work).

6. Conclusion

This thesis aimed to fill the gaps in the research of LT kinematic measurement, kinematic testing, and uncertainty determination. The first part provides a comprehensive summary of the influencing factors and error parameters concerning kinematic measurement, supplemented by additional errors affecting the kinematic measurement. Next, the existing LT testing procedures are described. However, many of these procedures are mainly dedicated to LT static measurement, showing a lack of suitable kinematic testing procedures.

In the second part, three individual experiments were conducted to assess and describe the LT kinematic performance. The first experiment shows the method for calculating the time delay between distances and angles by measuring fast oscillating moving targets. The results show that the time delay is zero for most of the experiment configurations. The only exception was when the movement acceleration amplitudes ranged from 10 to 12 m/ s^2 with 20 Hz frequency. Under this configuration, the time delay was calculated between 8 and 10 milliseconds. A second experiment with different LT and a similar setup verified the results with similar outcomes.

The second experiment was aimed at uncertainty modeling for measured quantities (distances and angles) during kinematic measurement. Most of the experiment configurations show that the kinematic uncertainty matches the static uncertainty declared by the manufacturer. However, there are specific acceleration amplitudes and frequencies that provide worse results, most probably because of the PSVC device.

For the third experiment, a new methodology for kinematic field testing was proposed and performed. The main idea of such testing is to allow users to quickly check the LT kinematic performance in the shop floor. The proposed methodology included the invention of a new testing prototype consisting of the rotating wheel with the mounting system. The prototype is easy to assemble, use, transport, and financially favorable for manufacture. The proposed methodology can be performed almost everywhere and within a few minutes to provide information about the LT kinematic performance.

Research contributions

- Vast description of LT kinematic measurement's error sources, along with developed error models and testing procedures.
- Determination of the time delay between measured angles and distances.
- Calculation of the LT kinematic uncertainty,
- Development of the methodology for the kinematic field testing, along with the new testing equipment.
- Analyses were performed on the real (not simulated) data acquired from experiments, which helped to identify some interesting findings about the instrument.

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