

**Procedure for calibration of laser tracker alignment errors
using a network measurement:
NIMTech deliverable 3.1(1)**

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Procedure for determination of laser tracker alignment errors using a network measurement

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Approved on behalf of NPLML by Dr Andrew Lewis, Assistant Knowledge Leader,
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1 SCOPE

This report forms deliverable 3.1(1) of the iMERA Plus project New Industrial Metrology Techniques (NIMTech). The report describes a method for calibration of laser tracker alignment errors using a network measurement approach.

2 INTRODUCTION

A laser tracker is a coordinate measuring system that tracks a moving target reflector and measures the position of the target in spherical coordinates (d , θ , ϕ). The radial distance, or range component, d , is typically measured by an interferometer (IFM) or an absolute distance meter (ADM). The IFM or ADM laser beam is steered to track the moving target by a motorised gimbal mechanism. Angle encoders on the mechanism provide azimuth, θ , and elevation angles, ϕ , to the target.

The implementation of the beam steering mechanism within the laser tracker varies from manufacturer to manufacturer, but they are all subject to misalignments, offsets and eccentricities that lead to errors in the measured coordinates. For this reason, all laser tracker manufacturers provide a means for correcting these errors in software. The correction software relies on a model that describes the beam steering mechanism and its errors, so the models and model parameters vary slightly from manufacturer to manufacturer. Loser and Kyle [1] described an error model applicable to a beam steering mechanism based on a gimballed mirror. More recently, Muralikrishnan *et al* [2] (from here on referred to as the NIST paper) modified this model to describe a laser tracker with the laser source on-axis in the rotating head.

The error correction software needs error parameter data that is usually derived from a combination of factory calibration and simple procedures that can be performed by the instrument user on the shop floor. The trade-off between time and complexity means that end-user procedures are not able to capture all the errors in the tracking mechanism simultaneously.

Drift or miss-calibration of the mechanical errors of the instrument result in measurement errors that are not easily detectable by the end-user. Standards exist [3, 4] that address performance verification of laser trackers using tests that are potentially performable by end-users. Specifically the standards prescribe tests aimed at comparing the length measurement capability of an instrument against an MPE. The result of these tests is a pass or fail; the instrument performs within MPE or it doesn't. These tests can show the effect of alignment errors within the tracker mechanism, but are not able to identify the individual error sources. Moreover the tests take several hours to complete and, as the NIST paper shows, the ASME B89 test [3] is insensitive to some of the mechanical alignment errors.

In this report and the accompanying data processing software, we present a simple test that is able to determine all the alignment errors of a laser tracker described in the NIST paper. The test requires no specialist equipment and can be performed by an end-user in less than 30 minutes.

The mathematical model of the laser tracker is described briefly in Section 3. A more detailed description of the error model and how it is solved is included in [5]. Section 4 covers the experimental procedures that we recommend.

3 LASER TRACKER ERROR MODEL

In this section we describe our error model. It is based very closely on the NIST paper, but with some differences. For comparison purposes, we cross-reference the error parameters used by the NIST model with those of the NPL model in Table 1.

For a detailed explanation of these errors the reader is directed to the NIST paper.

Table 1 Laser tracker error model parameters.

Error description	NIST parameter	NPL parameter
Beam offset	x_{1t}	$-h_2$
“	x_{1m}	$-h_9$
Transit offset	x_2	$-h_1$
Vertical Index offset	x_3	$-h_{10}$
Beam Tilt	x_{4t}	$-h_3$
Transit Tilt	x_5	$-h_4$
Encoder Eccentricity	x_{6x}	$-h_5$
“	x_{6y}	$-h_6$
“	x_{7mm}	$-h_{11}$
“	x_{7z}	$-h_{12}$
Bird Bath Error	x_8	$-\lambda$
Encoder scale	x_{9a}	$-h_7$
“	x_{9b}	$-h_8$
“	x_{10a}	$-h_{13}$
“	x_{10b}	$-h_{14}$

The NIST error model is:

$$R_c = R_m + x_2 \sin V_m + x_8$$

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

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

where, R_c , H_c and V_c are the corrected range, azimuth and elevation readings and R_m , H_m and V_m are the un-corrected range, azimuth and elevation readings and the parameters, x_i , are the instrument error parameters listed in Table 1.

We have modified this model slightly in the following ways:

1. Re-defined the elevation angle zero to be horizontal rather than vertical.
2. Introduced noise terms, ε_D , ε_A and ε_E , on all the measured data. These are samples from a statistical distribution with an expectation of zero and standard deviations of σ_D , σ_A and σ_E respectively.
3. Introduced a scale error, μ , on the range measurement.

The NPL model is:

$$d = (1 + \mu) d^* + \lambda + h_1 \cos \varphi + \varepsilon_D$$

$$\theta = \theta^* + \frac{h_2}{d \cos \phi} + \frac{h_3}{\cos \phi} + h_4 \tan \phi + h_5 \cos \theta - h_6 \sin \theta + h_7 \sin 2\theta + h_8 \cos 2\theta + \varepsilon_A$$

$$\varphi = \varphi^* - \frac{h_9}{d} + \frac{h_1 \sin \varphi}{d} + h_{10} + h_{11} \sin \varphi - h_{12} \cos \varphi + h_{13} \sin 2\varphi - h_{14} \cos 2\varphi + \varepsilon_D$$

where d , θ and ϕ are observed values and d^* , θ^* and ϕ^* are true values of the measurands. (Note that we have the observed values on the left hand side and NIST have the true values on the left - the signs of the parameters are therefore different between the models, hence the minus signs in Table 1.)

3.1 CORRELATED PARAMETERS

It is interesting to note the strong correlation between the birdbath distance, λ , and the transit offset, h_I , in the first equation. This correlation requires specific action to be taken during the measurements to weaken the correlation to allow each parameter to be evaluated.

4 EXPERIMENTAL PROCEDURE

The procedure is based on measurement of a network of fixed target points from multiple laser tracker positions. A network refers to a number of fixed points within a volume that have can be measured using an instrument (or instruments) from multiple locations and the data fitted together to form a consistent dataset. A significant advantage of this approach is that the inherent data redundancy leads to the ability to estimate the measurement uncertainty associated with the fitted parameters of the model as well as providing extensive diagnostic capabilities.

This section describes the design and simulation of an experimental setup, the measurement procedure and data processing.

4.1 EXPERIMENTAL SETUP AND DESIGN

Equipment

- The laser tracker
- 1 spherically mounted retro-reflector (SMR)
- 15 to 20 drift nests
- Hot-glue gun + glue sticks
- Tripod

The following criteria should be used when designing the network:

1. The number of target points should be reasonably small so that measurement time could be minimised.
2. The number of tracker positions required should be minimised to reduce measurement time.
3. The target points should be easily reachable by an operator holding an SMR.
4. The volume occupied by the network should be small. For example 4 m x 4 m x 2.5 m (high).
5. The network should test the tracker over a large angular range, both horizontally and vertically.
6. The network should be something that could be set up in a typical working environment.

The network that meets these requirements can be realised in the corner of a room as follows:

- A room with block or brick walls should be chosen for stability.
- A total of 15 to 20 drift nests should be used as target holders. They should be fixed securely to the walls and floor. Hot-glue can be used for temporary fixing. Alternatively, targets could be permanently fixed in place for more frequent testing purposes.
- The drift nest targets should be spread over the walls, with some close to floor level and some as high as can be easily reached.
- One target holder should be placed near the centre of the volume on a sturdy tripod. The position of this target should be chosen such that the tracker can be located at two positions along that line: one between the two points and outside the two points. (see Figure 1 and Figure 2). When the tracker is located between these two points, it should be tilted along the direction of the line as far as possible. This is necessary to weaken the correlation between λ and h_I described in section 3.1.

- The targets should all be measured from all tracker locations. At each location the tracker should be set at a different height and different azimuth angle orientations. Figure 3 and Figure 4 shows several views of an example set-up.

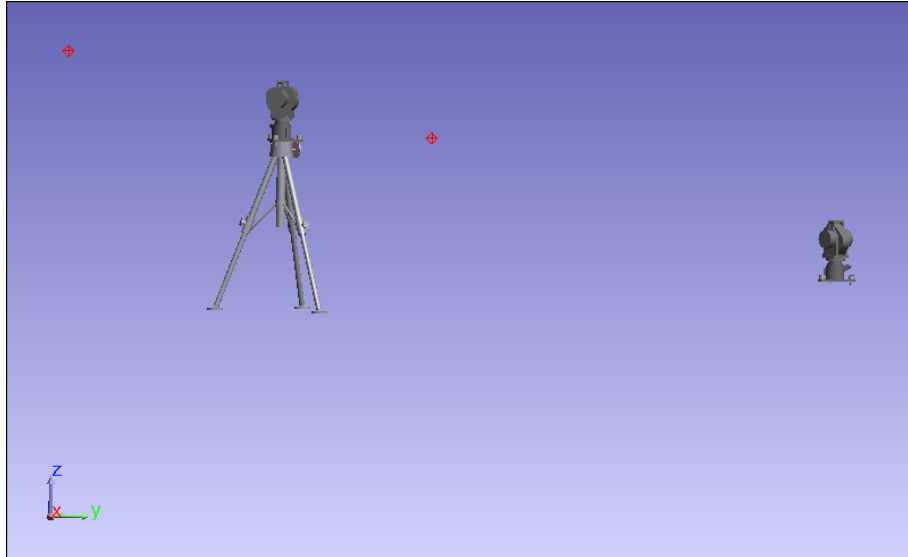


Figure 1 Elevation view showing two target points on a diagonal line. The point on the left is on a wall, the point on the right is on a tripod in the middle of the volume. The tracker can be placed in-line with the two points at the two positions shown. Note that when placed between the target points the tracker should be tilted as far as possible in the direction of the line joining the points.

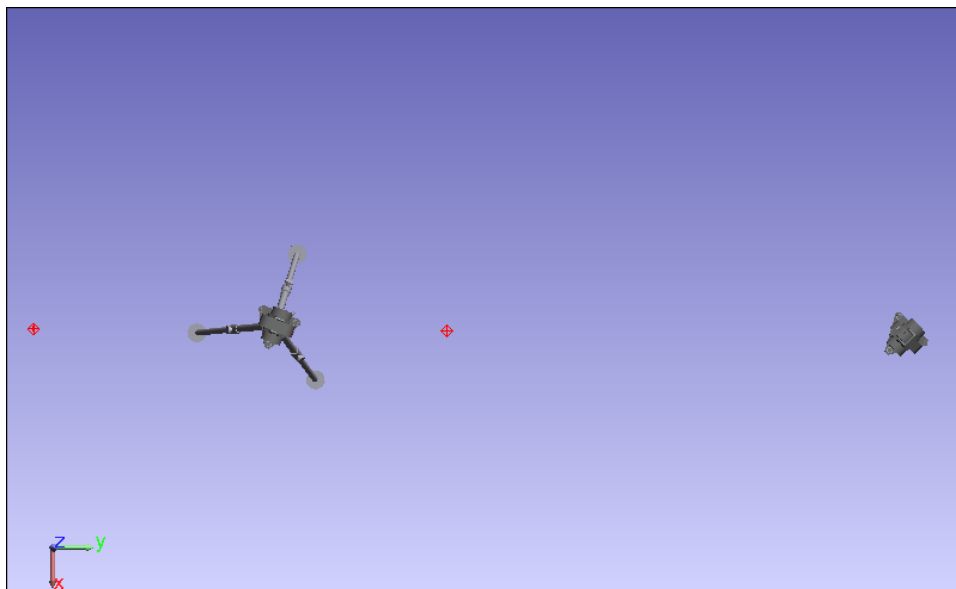


Figure 2 Plan view of the set-up show in Figure 1.

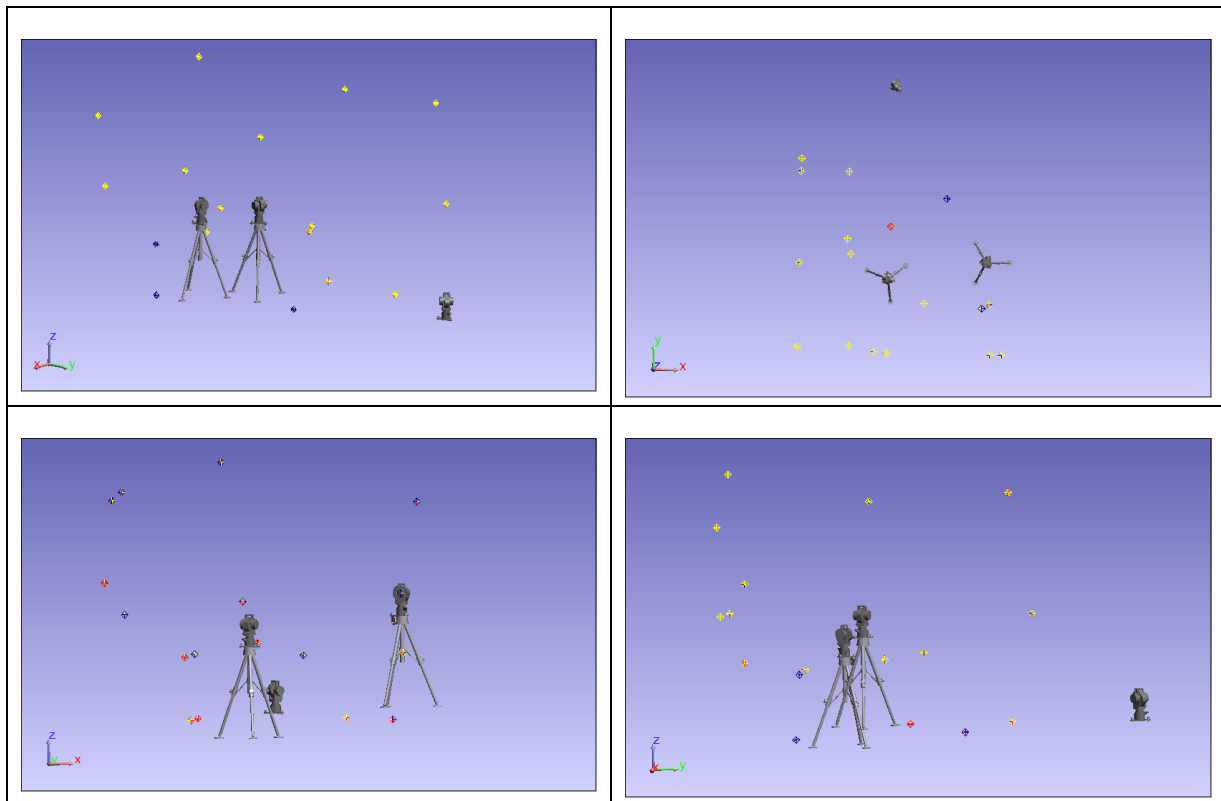


Figure 3 Views of the complete network setup.

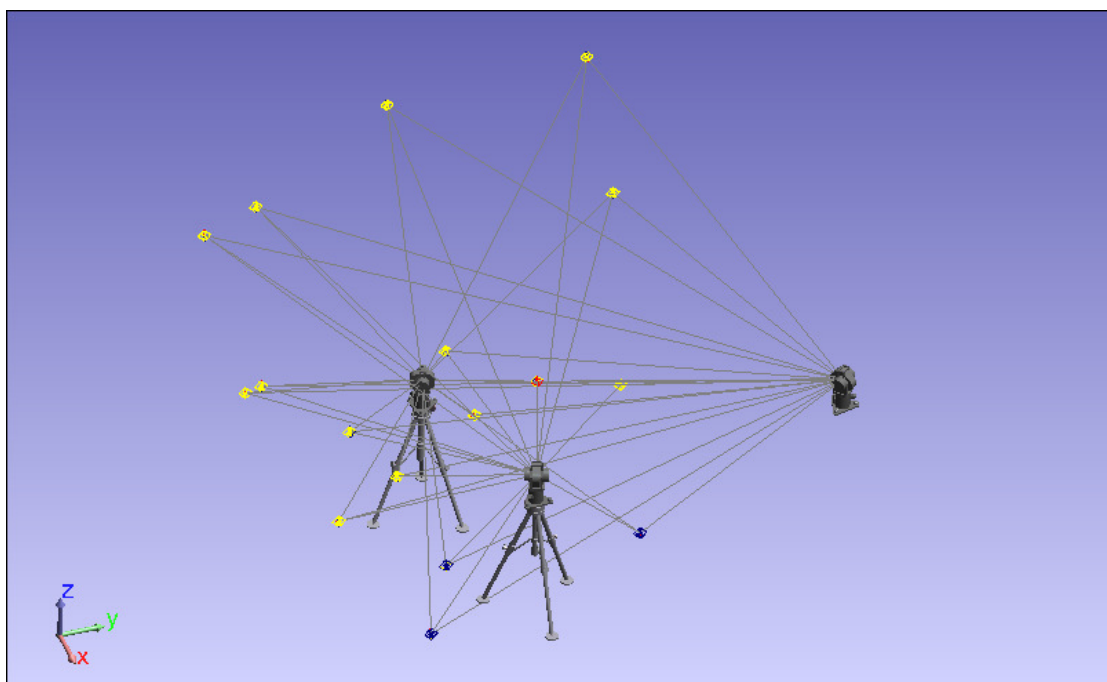


Figure 4 The complete network showing the shots from each tracker position to each target.

4.2 MAKING THE MEASUREMENTS

The following guidelines should be enforced when performing the measurements:

- Ensure all nests and the SMR are kept **clean**
- Make sure that the tracker and target tripods are **not knocked**
- Locate the weather station sensors within the volume of the network, but do not position the thermometer close to the tracker
- If using the ADM for measurement it should be calibrated against an IFM prior to making the measurements
- Complete the measurements as **quickly as practicable** to minimise drift in target positions due to thermal changes
- At each target point record **three** measurements. Each measurement should itself be an average of many samples e.g. three hundred samples over 3 seconds.

4.3 DATA PROCESSING

The measurement data recorded should be mathematically fitted - in a least-squares sense - to a mathematical model describing the experimental set-up and the alignment errors of the instrument. A description of the mathematical model is given in [5].

5 REFERENCES

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² B. Muralikrishnan, D. Sawyer, C. Blackburn, S. Phillips, B. Borchard, and W. T. Estler, ASME B89.4.19 Performance Evaluation Tests and Geometric Misalignments in Laser Trackers, J. Res. Natl. Inst. Stand. Technol. **114**, 21-35 (2009).

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⁴ VDI/VDE 2617 Blatt 10, 2009

⁵ Forbes A, Hughes B, Sun W, A model for laser tracker calibration, Technical Annex for D3.1.1, NIMTech JRP.