Performance Evaluation of Laser Trackers

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ABSTRACT

The American Society for Mechanical Engineers (ASME) recently released the ASME B89.4.19 Standard [1] on performance evaluation of spherical coordinate instruments such as laser trackers. At the National Institute of Standards and Technology (NIST), we can perform the complete set of tests described in the Standard, and have done so for a variety of laser trackers. We outline the tests described in the Standard, discuss our capabilities at the large-scale coordinate metrology group, and present results from B89.4.19 tests conducted on a few trackers. We also outline an analysis approach that may be used to evaluate the sensitivity of any measurement, including the tests described in the B89.4.19 Standard, to different geometric misalignments in trackers. We discuss how this approach may be useful in determining optimal placement of reference lengths to be most sensitive to different geometric misalignments.

Keywords

ASME B89.4.19, large-scale metrology, laser tracker, performance evaluation, sensitivity analysis

1. INTRODUCTION

Spherical coordinate measurement systems such as laser trackers, scanners and other devices are increasingly used in manufacturing shop floors for inspection, assembly, automation *etc*. These instruments are also sometimes used in the calibration of other lower-accuracy instruments such as industrial robots and even certain Cartesian coordinate measuring machines (CMMs). The spherical coordinate systems provide high accuracy at relatively low cost (in comparison to more conventional Cartesian CMMs), and are portable and convenient to use. Because of the proliferation of such devices in recent years, there has been an increasing need for a uniform set of performance tests so that users and manufacturers share a common understanding of the capabilities of the instrument.

In 2007, the American Society for Mechanical Engineers (ASME) published the ASME B89.4.19 Standard titled "Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems". This Standard, for the first time, defined a common set of tests that can be performed by both the user and the manufacture to establish if an instrument meets the manufacturer's performance specifications (MPE). This Standard, although limited to instruments that use a cooperative target such as retro-reflector, represents a significant step forward. It is the first and to date, the only performance evaluation Standard for spherical CMMs and establishes a framework for testing and evaluation of laser trackers and related devices.

In this paper, we present an overview of the B89.4.19 Standard and highlight the different tests described in it. We discuss capabilities of the large-scale coordinate metrology group at NIST where a complete set of B89.4.19 tests may be performed. We show examples of laser trackers tested at NIST that meet the manufacture's performance specifications and others that do not. Systematic errors due to geometrical and optical misalignments within a tracker are a major source of uncertainty in tracker measurements. An ideal performance evaluation test has high sensitivity to all misalignment parameters in a tracker's error model. Given the error model, it is possible to numerically determine the sensitivity of each of the B89.4.19 tests to different misalignment parameters. We have performed such analysis and briefly discuss our method and results.

2. THE ASME B89.4.19 STANDARD

The ASME B89.4.19 Standard describes three types of tests to be performed on trackers to evaluate their performance. These are the ranging tests, the length measurement system tests and two-face system tests.

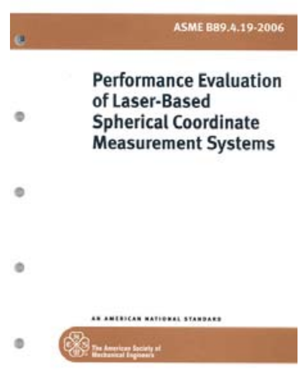

Figure 1. The ASME B89.4.19 Standard.

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2.1 Ranging Tests

Ranging tests assess the distance (or displacement) measurement capability of the instrument. The ranging system (an interferometer or an absolute distance measurement (ADM) system) establishes the unit of length and is therefore a critical component of the system. The tests as described in the Standard require the tracker to measure several calibrated lengths aligned along the line-of-sight of the tracker. The reference lengths employed may be calibrated artifacts, realized by free standing targets, or a laser-rail system.

2.2 Length Measurement System Tests

The length measurement system tests are similar to volumetric length tests on Cartesian CMMs. A calibrated reference length is placed at different positions and orientations in the measurement volume and is measured by the tracker. The error in the measured length is compared against the MPE to determine conformance to specification. There are several sources of mechanical and optical misalignments within the construction of a tracker that produce systematic errors in the measured angle and range readings and therefore in measured lengths. The length measurement system tests are designed to be sensitive to these misalignments. Again, the reference lengths employed may be calibrated artifacts, realized by free standing targets, or a laser-rail system.

2.3 Two-face System Tests

Some geometric misalignments are such that the errors in the measured angles of a fixed target change in sign when the same target is measured in the backsight of the instrument. Such frontsight-backsight measurements of a single target are called two-face tests. These tests are extremely useful because they capture a large number of geometric misalignments and they do not require a calibrated reference length. The Standard requires two-face tests to be performed at different positions within the work volume of the instrument. More details on the test positions may be found in [1,2].

3. LARGE-SCALE METROLOGY AT NIST

The large-scale coordinate metrology group at NIST has the capability of performing the complete set of B89.4.19 tests.

The ranging tests are performed in the 60 m long-length test facility where a laser-rail and carriage system is operational (see Figure 2). The carriage has two opposing retro-reflectors. One retro-reflector is used for the tracker under test while the other is used for the reference interferometer on the other end of the rail. The expanded uncertainty (k = 2) of reference length L is $U(L)$ = 5 μm + 0.3 × $10^{-6}L$.

Figure 2. The NIST 60 m laser rail facility viewed from the tracker under test end; note the movable carriage with retroreflector.

The length measurement and two-face system tests are performed in the large-scale laboratory. Currently, the reference length for the length measurement tests is realized using the laser-rail and carriage system (LARCS) [3] (see Figure 3). The LARCS (different from the 60 m laser-rail facility used for range calibration) employs a reference interferometer mounted on a rail (about 3 m long) that can be oriented in different ways (horizontal, vertical, inclined) to meet the B89.4.19 requirements. A carriage with two retro-reflectors rides on the rail. The tracker uses one retro-reflector while the reference interferometer utilizes the other. The expanded uncertainty (k = 2) of a nominal reference length L is $U(L)$ = 3.4 μm + 0.5 × 10^{-6} L for the LARCS system. We are now evaluating different artifacts that may be used as the reference length instead of the LARCS system [4].

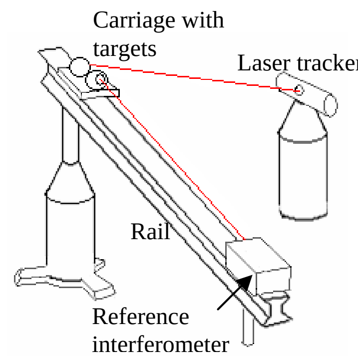

Figure 3. The LARCS laser rail.

4. TRACKER CALIBRATION EXAMPLES

We have performed the B89.4.19 tests on different trackers at our facility at NIST. Some trackers that were tested met the manufacture's specifications while others did not. We show results of ranging test performed on Tracker A in Figure 4. The data were recorded in the ADM mode of the tracker and substantially more points were recorded than required by the Standard. The errors in the measured lengths were within the manufacturer's specifications and therefore acceptable.

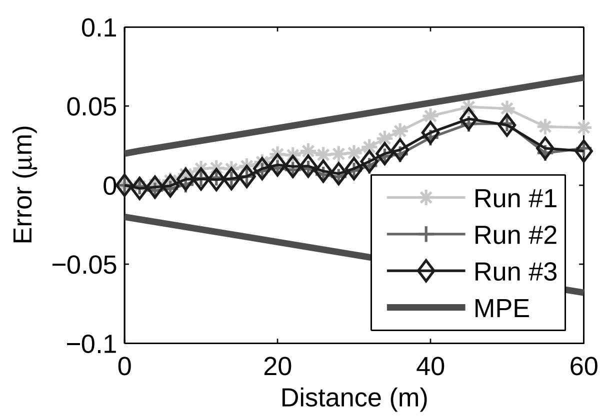

Figure 4. Ranging test results for Tracker A.

We present the results from the length measurement and two-face system tests for three trackers in Figures 5, 6, 7, 8, 9, and 10.

The length measurement system test charts (Figures 5, 7, and 9) may be interpreted as follows. The 35 length tests are in the order in which they appear in the Standard. Test 1 is the horizontal length measurement at the near position (1 m away, azimuthal angle of 0°). Tests 2 through 5 are the horizontal length measurements at four orientations of the tracker (0°, 90°, 180° and 270°) at the 3 m distance.

Tests 6 through 9 are the horizontal length measurements at four orientations of the tracker at the 6 m distance. Tests 10 through 17 are the vertical length measurements. Tests 18 through 25 are the right diagonal length measurements and tests 26 through 33 are the left diagonal length measurements. Tests 34 and 35 are the user-defined positions.

The two-face charts (Figures 6, 8, and 10) may be interpreted as follows. The 36 two-face tests are in the order in which they appear in the Standard. Therefore, tests 1 through 4 are the two-face measurements at the near position (1 m) with the target on the floor for four orientations of the tracker (0°, 90°, 180° and 270°).

Tests 5 through 8 are the two-face measurements at the near position (1 m) with the target at tracker height for four orientations of the tracker. Tests 9 through 12 are the two-face measurements at the near position (1 m) with the target at twice the tracker height for four orientations of the tracker (0°, 90°, 180° and 270°).

Tests 13 through 24 are a repetition of tests 1 through 12 but with the tracker 3 m away from the target. Tests 25 through 36 are a repetition of tests 1 through 12 but with the tracker 6 m away from the target. We discuss the tracker performance evaluation results next.

4.1 Tracker A

Tracker A (see Figures 5 and 6) clearly meets the manufacture's specification for length measurement and two-face system tests. The error in the measurement of a calibrated 2.3 m length placed 6 m away from the tracker was less than 25 μm, well under the manufacturer's specification of 100 μm. Small two-face errors, under 50 μm, for this tracker indicate that most of its geometric errors have been properly compensated.

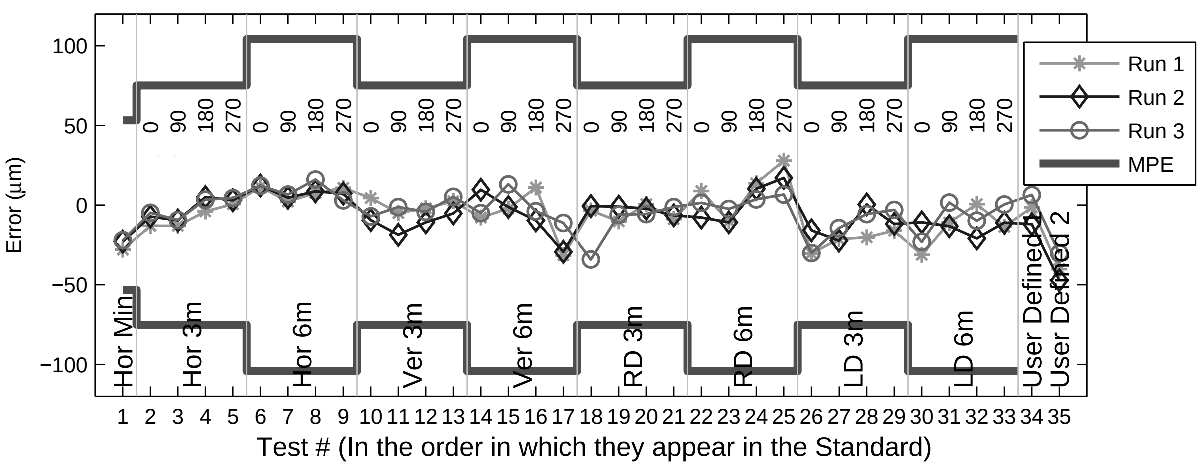

Figure 5. Length measurement system test results for Tracker A.

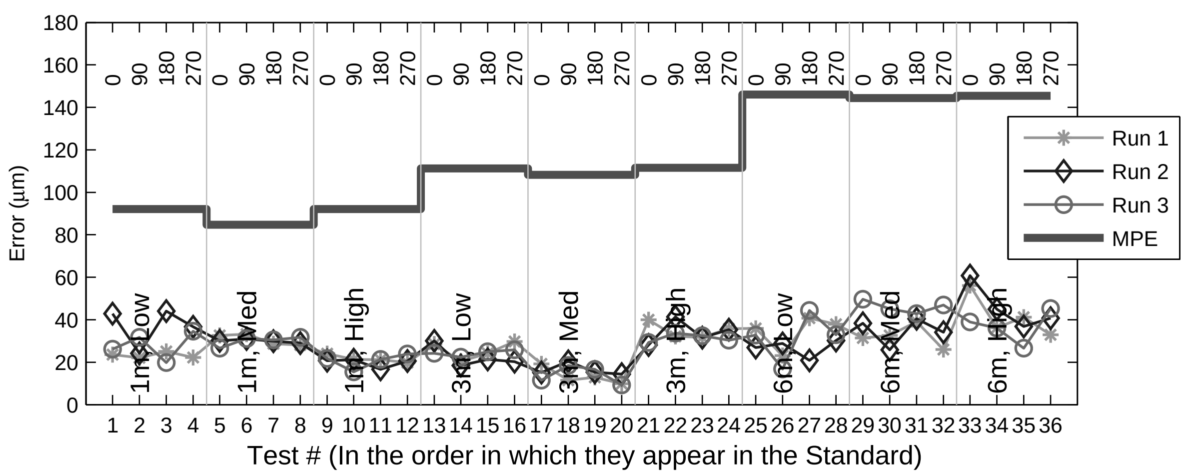

Figure 6. Two-face system test results for Tracker A.

4.2 Tracker B

Figures 7 and 8 show the results of length measurement and two-face system tests for Tracker B. This tracker appears to have satisfactory length measurement performance, but demonstrates large two-face errors.

Notice that the two-face error (Figure 8) demonstrates periodicity that is a function of the azimuth. In addition, the average two-face error (approximately 1.2 mm in Figure 8) does not change with distance of the target from the tracker. The average two-face error with increasing distance may arise from an offset in the beam from its ideal position (Tracker B does not have a beam steering mirror. Rather, the source is located directly in the head). Such an offset will result in decreasing error in the measured angle farther away from the tracker; consequently, the two-face error will be independent of range.

An explanation for the periodicity in the measured two-face data involves some subtlety. An eccentricity in the horizontal angle encoder will result in two-face errors showing periodicity that is a function of the azimuth. A least-squares fit of the data will therefore provide an estimate of the eccentricity. However, it turns out that when the two-face error, which is a convolved distance from horizontal and vertical angle error, is isolated into its constituent angle errors, the periodicity is in the vertical angle error. The vertical angle encoder has no functional relationship with the horizontal angle and therefore, the periodicity does not appear to be due to a geometric misalignment. The observed periodicity may be the result of stressing and relaxation of tension in cables within the tracker, or other such causes that are not considered in a geometric error model.

Although Tracker B did have large two-face errors, the B89.4.19 length measurement system test results (Figure 7) do not seem to be adversely affected by the large beam offsets. A careful consideration of the beam offset misalignment reveals that this term does not impact symmetrically placed lengths with respect to the tracker because the error at ends of the reference length cancel each other. Almost every B89.4.19 position is symmetrically placed with respect to the tracker. Asymmetrically positioned lengths will demonstrate large errors and may be used as the user-defined positions during the test.

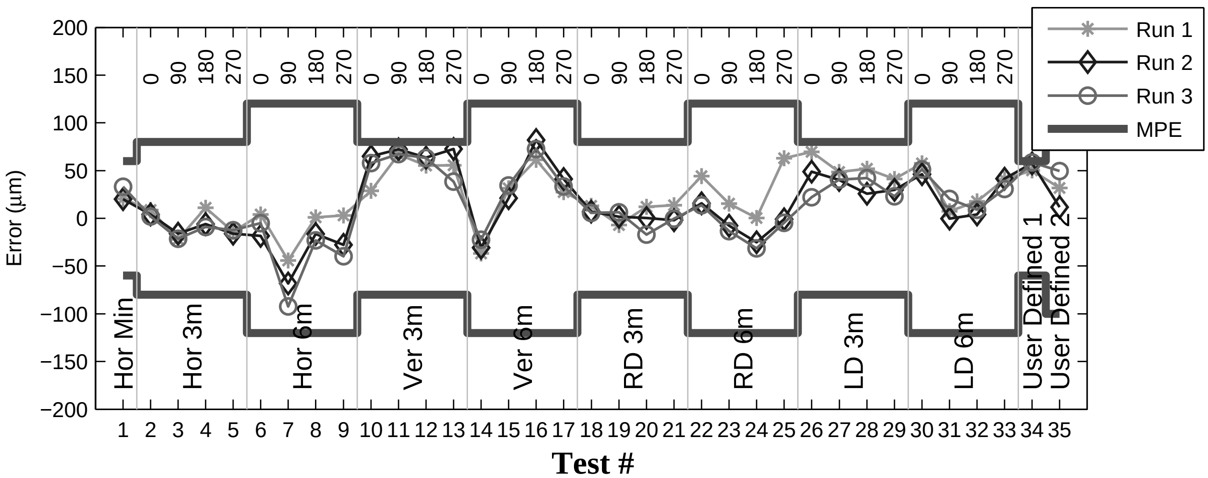

Figure 7. Length measurement system test results for Tracker B.

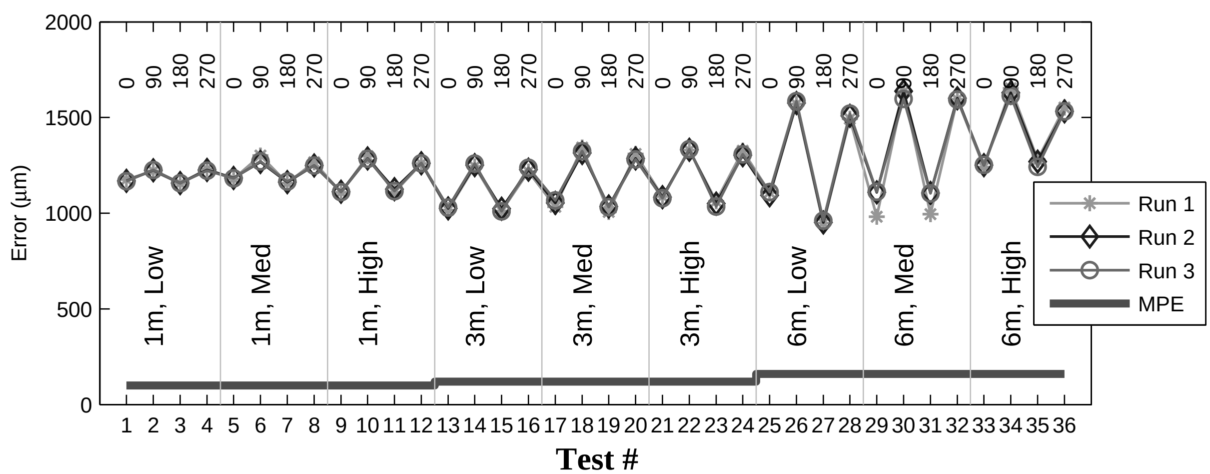

Figure 8. Two-face system test results for Tracker B.

Several interesting points raised in this section are worth summarizing:

- Large length measurement or two-face system test errors typically suggest that geometric misalignments have not been properly compensated.
- Two-face errors as reported in the B89.4.19 Standard are the convolved errors in both the horizontal and vertical angles, and scaled by the range. Raw horizontal and vertical angle errors from a two-face test contain more diagnostic information.
- The purpose of extracting the magnitude of physical misalignments from B89.4.19 tests is to estimate the error in other length measurements made within the work volume of the tracker.

4.3 Tracker C

Tracker C shows large errors in the length measurement system tests. The periodicity of the errors for Tracker C (Figure 9) may be the result of an eccentricity in the horizontal angle encoder, as well as a tilt in the beam as it emerges from its source. This tracker has the source located in the base and a beam steering mirror directs the beam to the target. Therefore, any tilt in the beam will also be a function of the azimuth. A least-squares best-fit may be performed to determine the magnitude of the eccentricity and tilt.

The two-face error (Figure 10) shows increasing error farther away from the tracker. A tilt in the beam as it emerges from the source will produce a constant angle error that when amplified by the range results in larger two-face error farther away from the tracker. We do not have the manufacturer's specification for two-face error for this tracker. The errors in Figure 10 are comparable to those of Tracker A and may therefore be acceptable, but nevertheless, there is evidence of improper compensation for geometric errors.

In this section, we have suggested that the B89.4.19 test results may be employed in a diagnostic mode where physical misalignments are determined. A geometric error model is required for this purpose. Error models are also useful in performing sensitivity analysis where the sensitivity of any given test to any geometric misalignment is determined through numerical simulation. We describe sensitivity analysis next.

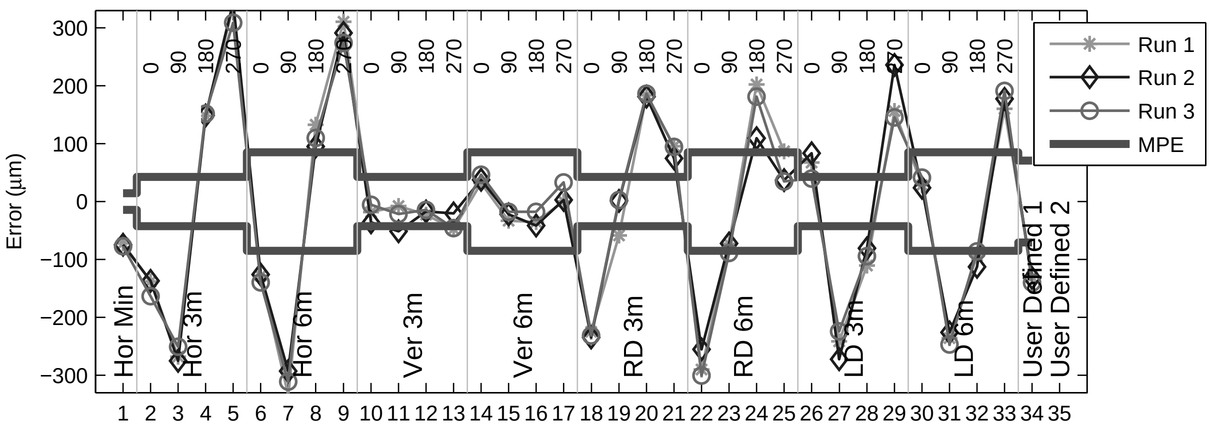

Figure 9. Length measurement system test results for Tracker C.

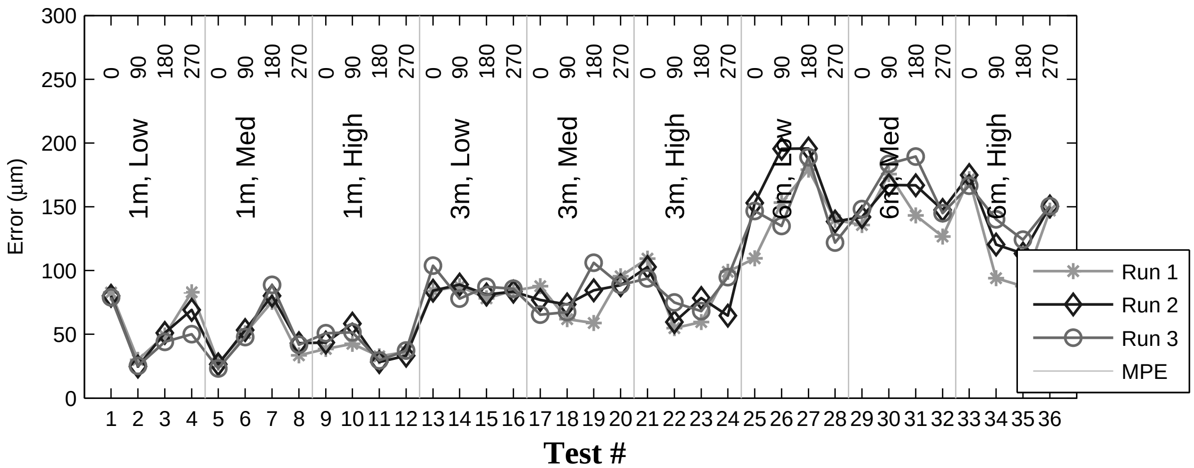

Figure 10. Two-face system test results for Tracker C.

5. SENSITIVITY ANALYSIS

A spherical coordinate instrument such as a laser tracker is a mechanical assembly of different components and therefore subject to misalignments such as offsets (offset in the beam from ideal position, offset between the standing and transit axes *etc*), tilt (tilt in the beam, tilt in the transit axis *etc*) and eccentricity (encoder eccentricity with respect to axis) during construction and assembly. It is general practice to correct for these misalignments by software compensation. A geometric error model [5] is required for this purpose that relates the corrected (true) range and angles to measured range and angles, and geometric misalignments within the tracker.

The corrected range (*Rc*) and angles (horizontal angle: *Hc*, vertical angle: *Vc*) of any coordinate in space are functions of several misalignment parameters within the construction of the tracker and also of the measured coordinate values at that location (*Rm*, *Hm*, *Vm*). The corrections ΔRm, ΔHm and ΔVm in *Rm*, *Hm* and *Vm* respectively may be expressed as (linear models may be sufficient as a first approximation),

$$\begin{aligned}
Rc - Rm &= \Delta Rm = \sum_{i=1}^{n} x_i u_i(Rm, Hm, Vm) \\
Hc - Hm &= \Delta Hm = \sum_{i=1}^{n} x_i v_i(Rm, Hm, Vm) \qquad (2) \\
Vc - Vm &= \Delta Vm = \sum_{i=1}^{n} x_i w_i(Rm, Hm, Vm)
\end{aligned}$$

where *x* is any misalignment parameter (eccentricity in encoder, beam offset, transit axis offset from standing axis, beam tilt, *etc*), and *u*, *v* and *w* are functions of measured range and angles.

Because different commercially available laser trackers have different mechanical constructions, an error model applicable to one tracker may not necessarily be applicable to another. At NIST, we have modeled three broad classes of trackers: a) tracker with a beam steering mirror for which the Loser and Kyle [5] model is applicable, b) tracker with the laser source in the rotating head and c) scanner with source mounted on the transit axis with a rotating prism mirror that steers the beam to the target.

As an example, an error model for a tracker with the source located in the head is given by

$$\begin{aligned}
Rc &= Rm + x_2.\sin(Vm) + x_8 \\
Hc &= Hm + \frac{x_{1t}}{Rm.\sin(Vm)} + \frac{x_{4t}}{\sin(Vm)} + \frac{x_5}{\tan(Vm)} + x_{6x}\cos(Hm) \\
&\quad - x_{6y}\sin(Hm) + x_{9a}\sin(m.Hm) + x_{9b}\cos(m.Hm) \qquad (3) \\
Vc &= Vm - \frac{x_{1m}}{Rm} + \frac{x_2\cos(Vm)}{Rm} + x_3 + x_{7n}\cos(Vm) \\
&\quad - x_{7z}\sin(Vm) + x_{9c}\sin(m.Vm) + x_{9d}\cos(m.Vm)
\end{aligned}$$

where x_{1t} and x_{1m} are beam offsets along the transit axis and its normal, x_2 is the transit offset, x_3 is the vertical index offset, x_{4t} is the beam tilt, x_5 is the transit tilt, x_{6x} and x_{6y} are the horizontal angle encoder eccentricities, x_{7x} and x_{7y} are the vertical angle encoder eccentricities, x_8 is the bird-bath error, and x_{9a}, x_{9b}, x_{9c} and x_{9d} are the components of the m^{th} order scale error in the encoder (1^{st} order is not distinguishable from encoder eccentricity. Higher orders beyond 2^{nd} order may be neglected).

This error model may now be used to numerically estimate the sensitivity of any given test to geometric misalignments that are included in the model. As an example, consider the beam offset terms. We describe how the coefficients for the parameters in the error model were obtained, and then discuss the sensitivity of different B89.4.19 tests to this misalignment.

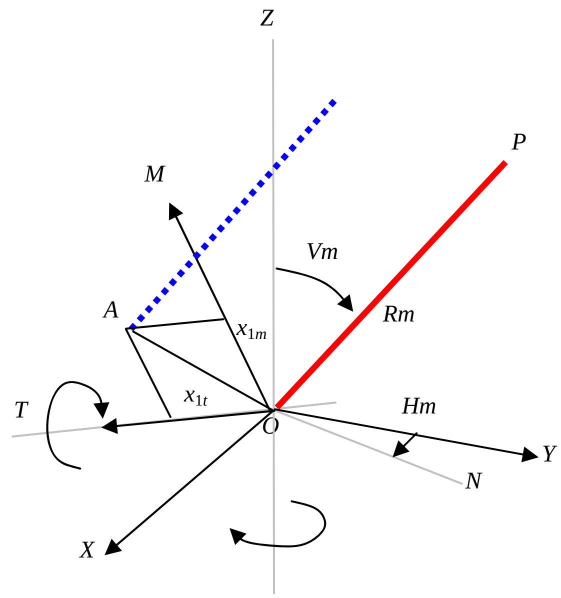

Figure 11. Schematic of beam offset in a tracker where the beam originates from the head (there is no beam steering mirror). Axes *OT*, *ON* and *OM* are fixed to the tracker's head and therefore rotate with the head about the *Z* axis.

5.1 Error Model Coefficients

The beam originating from the source (at *O*) may be displaced from its ideal position by a constant offset (*OA* in Figure 11) to emerge from *A*, a misalignment parameter referred to as beam offset. The offset can be resolved into components along two orthogonal axes, *M* and *T* (x_{1m} and x_{1t}). In Figure 11, *OT* is the transit axis, *P* is the target, *ON* is the projection of the beam to the target on the *XY* plane, and *OM* is the normal to both the transit axis and beam to the target. *XYZ* is a fixed Cartesian coordinate system with origin at *O*. *TNZ* is Cartesian coordinate system, also with origin at *O*, but attached to the tracker head so that it can rotate about the *Z* axis. *TPM* is also a Cartesian system with origin at *O* and attached to the tracker so that it can rotate about the transit axis *OT*. The offset component along the transit (x_{1t}) produces an error in the measured horizontal angle. The correction for the beam offset is given by $\Delta Hm = \dfrac{x_{1t}}{Rm.\sin(Vm)}$.

The component along its normal (x_{1m}) produces an error in the measured vertical angle, and its correction is given by $\Delta Vm = \dfrac{-x_{1m}}{Rm}$.

5.2 Sensitivity to Two-face System Tests

The effect of beam offset on two-face tests described in the B89.4.19 Standard can be determined as follows. The corrections for the measured horizontal and vertical angles of a target placed distance *Rm* away from the front face of the tracker are given above. These corrections reverse in sign when the tracker is in the backsight mode. The apparent distance *E* in a two-face test is therefore given by $E = 2\Delta Hm.Rm.\sin(Vm) = 2x_{1t}$ for offset along the transit axis and $E = 2\Delta Vm.Rm = 2x_{1m}$ for offset along *OM*. Both beam offset parameters are therefore sensitive to every two-face test described in the Standard by the same sensitivity factor of 2.

5.3 Sensitivity to Length Measurement System Tests

Systematic errors in measured range and angles lead to an error in the determination of the coordinates of each end of the reference length. This however does not necessarily imply an error in the calculated length between the two ends because the error vectors (vector between true coordinate and measured coordinate) at the two ends may simply result in translation and/or rotation of the length, but not a change in its magnitude. Sensitivity to length tests is achieved primarily if the error vectors at the two ends produce components along the length with non-zero sum. Components perpendicular to the length are generally not sensitive.

Any symmetrically placed reference length (such as the horizontal, vertical or diagonal length tests in the Standard) is not sensitive to beam offset because it only serves to translate and rotate the length. The default position for the first user-defined test (asymmetrical vertical length test) is sensitive to beam offset along the *M* axis because the asymmetrical positioning of the reference length creates unequal error components at the two ends of the reference length which do not completely cancel each other.

6. SUMMARY

The complete set of B89.4.19 tests may be numerically simulated and the sensitivity of each test to every parameter in the error model can be determined. The results, tabulated as a two-dimensional matrix with B89.4.19 tests in one axis and misalignment parameters in the other, is a "sensitivity matrix." We have created such sensitivity matrices for the three classes of trackers for which we have developed error models. Such matrices are useful in assessing the capabilities and limitations of any set of performance evaluation tests.

Analysis of such sensitivity matrices further leads to the identification of optimal length positions that are sensitive to specific geometric misalignments. For example, we mentioned that the beam offset misalignment parameter was not sensitive to horizontal, vertical, or diagonal length tests because of the symmetrical nature of the positioning of the reference length with respect to the tracker. Sensitivity analysis indicated that asymmetrical positioning is advantageous, and therefore may be considered as a user-defined test.

7. CONCLUSIONS

The recently released ASME B89.4.19 Standard provides a common set of performance evaluation tests that may be performed by both the manufacturer and the user to evaluate if the instrument meets the manufacture's specifications.

The Standard contains three types of tests. The ranging tests assess the instrument's distance (or displacement) measuring capability. The length measurement and two-face system tests identify any systematic errors within the instrument's construction, such as mechanical and optical misalignments. The length measurement system tests require a calibrated reference length (typically 2.3 m long) realized either as an artifact or using laser-rails, or between free standing targets calibrated by other means. The ranging tests require a reference interferometer and a laser-rail and carriage system where long lengths may be calibrated or some other means to independently measure long lengths reliably. The two-face tests require no reference lengths. They are simple and easy to perform, and capture a large number of geometric misalignments.

The B89.4.19 test results provide valuable diagnostic information as well. Using geometric error models of the tracker, it may be possible to estimate magnitudes of misalignments in the construction of the tracker. Such information may then be used in determining errors in other length measurements made within the work volume of the tracker.

Geometric error models also serve a more general role. They may be used to determine the sensitivity of any given test to any geometric misalignment within the tracker. Such sensitivity analysis is useful in determining if a given set of performance evaluation tests effectively captures the misalignments, or if any modifications in the placement of reference lengths are necessary.

8. REFERENCES

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