Choosing Test Positions for Laser Tracker Evaluation and Future Standards Development

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Abstract
A working group within the ISO TC 213 committee is developing a draft document [1] for evaluating the performance of laser trackers. The ASME B89.4.19 Standard [2] and the draft VDI/VDE 2617 part 10 [3] describe some useful tests that are incorporated into this new ISO document. But both the ASME and VDI/VDE documents also have some limitations. The new ISO draft document, which is currently under consideration by the committee, draws from the key attributes of the ASME B89.4.19 and the draft VDI/VDE 2617 part 10 while eliminating weak or redundant tests. The approach to selecting suitable tests is based on the sensitivity of each test to different geometric misalignments in different tracker designs. We discuss the proposed ISO draft document in this paper.

1. Introduction

A laser tracker task force within the ISO TC 213 WG10 committee is currently working on a draft document for an international Standard on laser trackers. The task force includes experts involved in laser tracker metrology from several countries (US, Germany, Japan, Austria, etc). One major topic of discussion is the number and type of tests to be included in the draft ISO document. There are at least two excellent documents that serve as starting points for this purpose, the ASME B89.4.19 Standard and the draft VDI/VDE 2617 part 10.

Both the ASME B89.4.19 and the draft VDI/VDE 2617 have strengths and weaknesses. The task force has attempted to draw from the strengths of the two documents while eliminating their weaknesses and redundancies. The working draft, currently out for voting to become a Committee Draft (CD), contains a core set of tests that exhibit sensitivity to different geometric/optical misalignments in laser trackers. This core set of tests was determined from a sensitivity analysis performed using mathematical error models for different tracker designs. In addition to the core set, the proposal contains a required supplemental set; there are two default options for this supplemental set, one of which is drawn from the B89.4.19 Standard and the other is from the draft VDI/VDE 2617 part 10. Individually, each test is comprised of a measurement of a single calibrated reference length. The overall number of proposed measured reference lengths is 105, to be consistent with the number of tests in the ISO 10360-2 Standard [4]. In the following sections, we briefly describe a sensitivity analysis based method illustrating the strength of the proposed ISO approach and provide examples of its effectiveness; we also point out the strengths and weakness of the ASME B89.4.19 and the draft VDI/VDE 2617 part 10.

2. Sensitivity Analysis Based Approach

There are many different geometric and optical misalignments within a tracker that lead to systematic errors in the measured range and angles of a target. Tracker manufacturers generally include geometric error compensation models within their

software to account for some of these errors. The parameters of these models are determined from compensation procedures performed prior to a measurement.

If the error models are carefully constructed from a study of different tracker error sources, they can also be useful in identifying laser tracker tests that are sensitive to the different sources of error that constitute the error model. We have described error models and the sensitivity analysis based method in [5]; a detailed description is beyond the scope here. To illustrate how the technique may be useful in detecting tracker errors, we present two examples where through appropriate positioning of the reference lengths the test becomes sensitive to specific geometric misalignment terms.

Example 1: An offset beam in a tracker without a beam steering mirror:

For an ideally constructed laser tracker, the laser beam emerges from the point of intersection of the standing (vertical) and transit (horizontal) axes of the tracker. But if the beam emerges with an offset from these axes, there may be an error in the horizontal and vertical angle readings. We consider the component of the offset in the vertical plane to illustrate our approach, see Fig. 1.

Fig. 1 (a) shows a symmetrically placed reference length *AB*. The ideal beam emerges from *O* and strikes one end of the length at *A* and the other end at *B*. The offset beam travels to A_1 and B_1.The errors at *A* (AA_1) and *B* (BB_1) are equal in magnitude and sign and therefore there is no net error in the length; the length only appears to be rotated by a small amount. A symmetrically placed length is therefore not sensitive to an offset beam.

Fig. 1 (b) shows an asymmetrically placed reference length *AB*. In this case, a component of the error AA_1 is along the

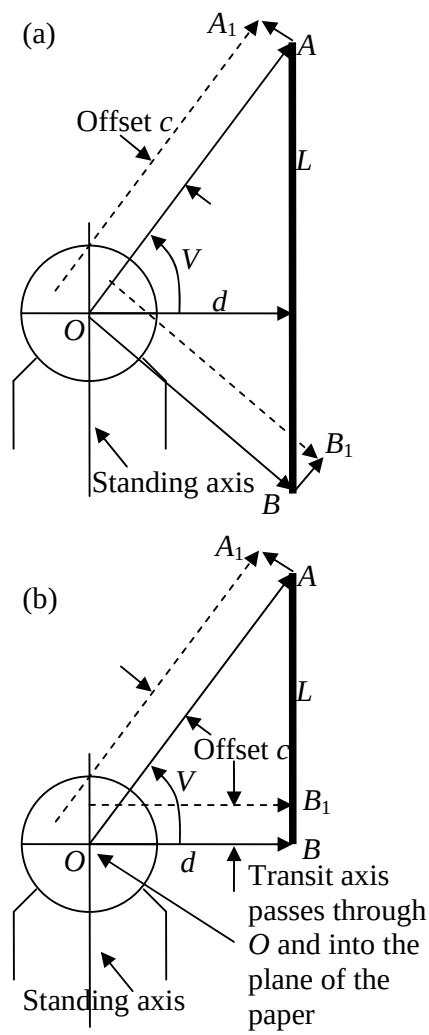

Figure 1 *(a) A symmetrically placed vertical reference length (AB) test is not sensitive to offset c because the errors at A (AA_1) and at B (BB_1) are equal in magnitude and sign resulting in a net zero error in the length (b) An asymmetrically positioned vertical reference length (AB) test is sensitive to offset c because only a portion of the error at A serves to cancel that at B resulting in a residual error.*

length and cancels some of the error at *B*, but there is still a residual error leading to some sensitivity to beam offset misalignment. A simple calculation may be performed to maximize the sensitivity as shown here. The net error in the length *E* is given by

$E = c(1 - \cos V)$, where c is the offset of the beam in the vertical plane. The sensitivity s, given as the ratio of the error in the length to the offset in the beam, is

$s = E/c = 1\text{-}\cos V$.

Clearly, s is largest when V tends to 90°; therefore for a given length L, it is desirable to place the length as close as possible to the tracker. This test position detects the error that would appear in a measurement of a large vertical length such as on the tail section of an aircraft.

Example 2: Eccentricity in the horizontal angle encoder:

Any eccentricity in the mechanical placement of the horizontal angle encoder relative to its axis of rotation will result in systematic errors in the tracker's horizontal angle reading. The error $e(\phi)$ in horizontal angle ϕ due to an eccentrically mounted encoder may be given by $a \cos\phi + b \sin\phi$ where (a, b) are the eccentricities along x and y [6]. The problem therefore is to identify a position and orientation for reference length L that maximizes the sensitivity to this misalignment. We will consider just the cosine term here, i.e, $e(\phi) = a \cos\phi$; a similar argument applies to the sine term.

Clearly, a horizontally placed reference length will be sensitive to this error source. Further, a symmetrically placed reference length will be preferable since the errors at two ends could potentially sum to produce twice the error. Some simple trigonometry from Fig. 2 yields the error in the length $E(\theta,\phi)$ as (see [7] for a more detailed explanation)

$$E(\theta,\phi) = R[e(\phi+\theta)\cos\theta - e(\phi-\theta)\cos\theta] = R\,a[\cos(\phi+\theta)\cos\theta - \cos(\phi-\theta)\cos\theta] = L\,a\cos\theta\sin\phi.$$

The sensitivity s, given as the ratio of the error in the length to eccentricity in the encoder, is therefore

$$s = E(\theta,\phi)/a = L\cos\theta\sin\phi.$$

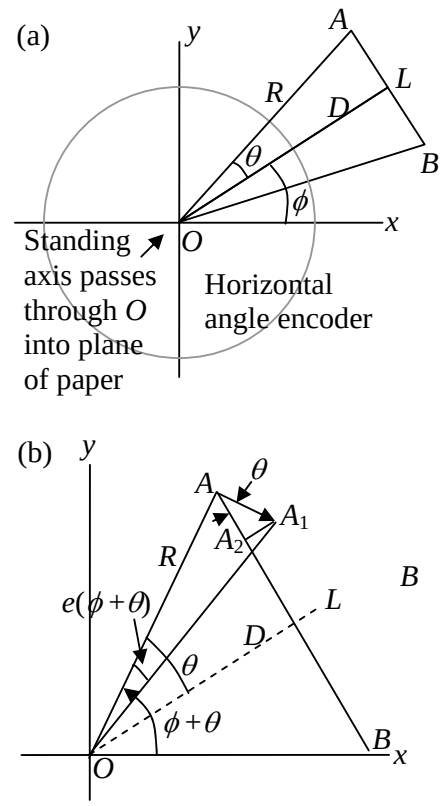

Figure 2 *(a) A horizontal reference length test to detect eccentricity in the horizontal angle encoder. The reference length AB is placed so that its bisector makes an angle ϕ with the x axis. The length subtends an angle 2θ at tracker O (b) A diagram showing the calculation of the errors in the length AB due to error in the horizontal angle from eccentricity in the encoder, see [7] for more details.*

For an artifact of length L, the sensitivity is largest when $\phi = 90°$, and θ is as small as possible. The angle θ cannot be zero since it is half the angle subtended by the length. But moving the length far away from the tracker will reduce this angle. There will of course be practical limits to how far away a length can be placed. A 3 m length placed 6 m away, as in the ASME

B89.4.19 Standard, produces a sensitivity equal to 97 % of the theoretical maximum sensitivity (which is realized when the length is placed infinitely far away) achievable for this 3 m length, and is sufficient for our purpose here in detecting eccentricity errors.

The above examples showed how understanding error sources and developing mathematical error models can aid in the selection of test positions that are sensitive to the different geometric errors. Another example is discussed in [7], where the placement of horizontal lengths is studied to achieve maximum sensitivity to second order scale errors in the horizontal angle encoder. We next discuss the strengths and weaknesses of the ASME B89.4.19 and the draft VDI/VDE 2617 part 10.

3. ASME B89.4.19

The ASME B89.4.19 is the only published and available Standard for laser trackers. The Standard includes three types of tests to be performed on trackers – ranging tests, length measurement system tests, and two-face system tests. We do not describe these tests here; a description may be found in the Standard [2] and in other publications [8, 9]. We focus on the strengths and weaknesses of this Standard here.

Strengths:

- The separation of the ranging tests from the volumetric length tests allow the testing of the ranging unit to its full extent and also allows for a smaller artifact length (such as the 2.3 m length) when testing volumetric performance.
- The incorporation of two-face tests offers a quick and effective check of the tracker's health. Two-face tests are ideal because they are sensitive to numerous tracker misalignment terms and require no artifact for their performance.
- Many tests described in the Standard are sensitive to different geometric/optical misalignments within the tracker. As one example, the horizontal length test performed at the four clocking angles (0°, 90°, 180° and 270°) is sensitive to the eccentricity of the horizontal angle encoder as discussed in the preceding section.

Weaknesses:

- There are several redundant tests in the Standard. For example, the vertical length test must be performed at 4 clocking angles (0°, 90°, 180°, and 270°) according to the Standard whereas for the known kinematic errors of current tracker designs only one position will suffice (the azimuth has no influence on vertical length measurements since it remains fixed during the measurement). It is not necessary to perform the diagonal length test at both the 3 m and 6 m distance. Higher sensitivity to squareness error is obtained at the 3 m position. Also the two-face tests at the 3 m distance are not necessary; the tests at 1 m and 6 m position will suffice in capturing the dependence of two-face errors on distance from the target.
- There is considerable symmetry in the placement of the lengths that result in poor or no sensitivity to numerous geometric misalignment terms in trackers. Examples of terms that show poor or no sensitivity include beam offsets and tilt, vertical index offset, one component of vertical encoder eccentricity, and a component of second order scale error in the horizontal and vertical angle encoder.

Improvements in the positioning of the reference length, such as introducing some asymmetry in placement, will improve the sensitivity of the test to different geometric

misalignments, as we have shown in [5]. The draft ISO document has incorporated this concept and includes the following tests: asymmetric horizontal length tests, asymmetric vertical length tests, asymmetric diagonal length tests, symmetrical horizontal lengths placed above the tracker, and a buck-in buck-out test (or a close approximation to it).

4. Draft VDI/VDE 2617 Part 10

The draft VDI/VDE 2617 part 10 proposes testing the tracker in a large volume by measuring different lengths placed in different orientations. In recommending these system level tests, the draft document treats the tracker as a black box without attempting to isolate errors in each axis.

Strengths:

- The draft requires the measurement of some very large lengths that may more closely resemble a laser tracker's intended application.
- There are some interesting positions that may be chosen in the measurement volume that are very sensitive to some error sources, such as a horizontal length placed 1.5 m away and 1.5 m below or above the tracker height that is sensitive to one component of the vertical angle encoder's eccentricity; this misalignment term is otherwise not easy to detect. Another useful test is to place the tracker inside the measurement volume and sight to two targets at opposite ends and in line with the tracker. This test will be sensitive to any zero error in the trackers ranging unit (bird-bath error) and any offset between the standing and the transit axes.
- The draft describes tests to estimate probe size and form error. These are useful tests since spherically mounted retro-reflector (SMR) errors may be large and require testing.

Weaknesses:

- This Standard allows considerable flexibility in choosing the test lengths. Therefore it is quite possible that a poor choice of lengths will not detect many tracker errors when in fact, the tracker may have large systematic errors. For trackers without a beam steering mirror, even a good choice of lengths will not be sensitive to collimation error. A Monte Carlo simulation suggested that there is considerable probability of choosing lengths that are not sensitive to beam offset as well. For a tracker with a beam steering mirror, there is high probability of not detecting cover plate offset (see [5, 6] for more information on these geometric misalignment terms).
- Because the ranging tests are not separated from the volumetric length tests, there is a need to perform measurements on some very large lengths. It can be quite tedious to calibrate such large lengths.
- Two-face tests are only suggested as a fast and intermediate test of the tracker, and are not required to be performed. In practice, the two-face tests are invaluable in diagnosing a tracker's health and should be performed as part of the testing procedure.

5. The Draft ISO Set of Tests

We discuss the tests described in the draft ISO document in this section. There are 105 reference lengths tested – to be consistent with the ISO 10360-2 Standard for Coordinate Measuring Machines (CMMs). Of these, the ISO document contains a core set of 41 tests (see Table 1) designed to be sensitive to all known opto-mechanical errors in the different designs of trackers currently available. The remaining 64 test lengths are user-defined tests. There are two default options; the first default option is drawn from the

ASME B89.4.19 and is listed in Table 2, the second default option is drawn from the draft VDI/VDE 2617 part 10 and is shown in Figure 4. The user is free to choose any other set of 64 test lengths as well.

5.1 Core Tests

It should be noted that each test position may be sensitive to more than one source of error, and further, the same test may exhibit different sensitivity to the same error source in a different tracker design. Any justification for the inclusion of a test will therefore involve multiple factors. In this paper we attempt to provide one principal reason for the inclusion of each test here. Fig. 3 shows some of the positions described in Table 1. A reference length 2.25 m to 2.75 m long may be used for the tests unless specifically indicated in Table 1.

Positions 1 and 2 are designed to test a large fraction of each of the angular axes of the tracker. These are included in the spirit of the ISO 10360-2 where each axis is tested for at least 66 % of its range. Further, position 1 also tests for bird-bath error and any offset between the standing and transit axes.

Positions 3 to 6 test for the eccentricity in the horizontal angle encoder, position 7 tests for one component of the vertical angle encoder eccentricity, positions 8 to 15 test for squareness between the standing axis and the transit axis, and positions 16 to 19 attempt to isolate the effect of combination of errors (for example, the effect of beam offset, beam tilt, and encoder eccentricity in a tracker with a beam steering mirror).

Positions 20 to 23 test for beam offsets along the horizontal direction, position 24 tests for beam offset along the vertical direction, positions 25 to 28 test for collimation error (for example, tilted beam in a tracker without a beam steering mirror), position 29 tests for another component of the vertical angle encoder's eccentricity, positions 30 to 35 test for low even order harmonics in the horizontal angle encoder's scale [7], and positions 36 to 40 test for ranging error in a tracker.

Position 41 is a synthetic length test and is described in the draft VDI/VDE 2617 part 10. The purpose of this test is to validate the temperature compensation capability of the tracker system. This is achieved as follows. A long length is realized between two nests and the distance between them is calibrated using an interferometer. The length is reported at 20 °C; let its value be L. It is now assumed that there exists a steel block of that length in the room whose temperature is T. Further assume that the thermal coefficient of expansion of the block is exactly 11.5 μm/m/°C. If the temperature of the room T is different from 20 °C, the block's length at 20 °C can be calculated as $Ls = L(1\text{-}11.5\text{x}10^{-6}\ (T\text{-}20))$. This 'synthetic length' Ls is the calibrated length of the hypothetical steel block at 20 °C; for this calculation the temperature T is determined by placing a temperature sensor on a block of steel that is in equilibrium with the room. The laser tracker is then used to measure the distance between the nests with an expansion coefficient of 11.5 μm/m/°C input in its software. As before, the temperature sensor of the laser tracker is made to measure the temperature of a block of steel which is in equilibrium with the room. The length obtained thus is compared against Ls to determine the error.

The 41 tests described in Table 1 comprise the core set of tests that is sensitive to known sources of geometric misalignments. It is preferable to have additional tests for several reasons:

- The ISO 10360-2 and ASME B89.4.19 Standards require three measurements to be performed at each position and

orientation of the reference length. There is no analogous repeatability measurement in our core set. The first default option in the supplemental set includes such repeatability tests.

- It is possible that the intended use of a tracker may be considerably different from any of the tests described in the core set. For example, the tracker may primarily perform long length measurements far away from the tracker. Therefore, the user may require such a measurement as part of the supplemental set. The second default option includes such long length measurements.
- There may be other sources of systematic error in a tracker not related to optical or geometric misalignments. Additional tests are therefore useful in detecting these errors.

Table 1 Core set of tests in the draft ISO document

Position number	**Distance *d* from tracker**	**Description of reference length position**	**Horizontal angle(s) with respect to the tracker (°)**
1	As close as practical	Horizontal, centered (i.e., the ends of the reference length are equidistant from the tracker), and at tracker height. This tests 66 % of the horizontal angle measurement axis of the tracker (see Fig. 3(a)).	at any azimuth
2	As close as practical	Vertical, center of the length is at tracker height (ends of the reference length are equidistant from the tracker). This tests 66 % of the vertical angle measurement axis of the tracker (see Fig. 3(b)).	at any azimuth
3-6	3 m	Horizontal, centered (i.e., the ends of the reference length are equidistant from the tracker), and at tracker height (see Fig. 3(a)).	0, 90, 180, 270
7	3 m	Vertical, center of the length is at tracker height (ends of the reference length are equidistant from the tracker) (see Fig. 3(b)).	0
8-11	3 m	Right diagonal, centered (i.e., the ends of the reference length are equidistant from the tracker), and the center of the length is at tracker height (see Fig. 3(g)).	0, 90, 180, 270
12-15	3 m	Left diagonal, centered (i.e., the ends of the reference length are equidistant from the tracker), and the center of the length is at tracker height (see Fig. 3(d)).	0, 90, 180, 270
16-19	6 m	Horizontal, centered (i.e., the ends of the reference length are equidistant from the tracker), and at tracker height (see Fig. 3(a)).	0, 90, 180, 270
20-23	As close as practical	Horizontal, not-centered (i.e, the tracker is directly in front of one end of the length), and at tracker height (see Fig. 3(e)).	0, 90, 180, 270
24	As close as practical	Vertical, not-centered (i.e, the tracker is directly in front of one end of the length) (see Fig. 3(c)).	0
25-28	As close as practical	Diagonal, one end is below or above the point directly in front of the tracker, the other end is at tracker height and to the right or left of the point directly in front of the tracker. The range to the two ends of the length is equal (see Fig. 3(f)).	0, 90, 180, 270
29		Horizontal, centered directly above (as much as that is possible) the laser tracker itself (see Fig. 3(h)).	0
30-35	Long[1]	Horizontal, centered (i.e., the ends of the reference length are equidistant from the tracker), at tracker height (see Fig. 3(a)).	0, 30, 60, 90, 120, 150
36-40	5 test distances	This tests 66 % of the ranging axis of the tracker.	
41		Synthetic length test	

[1]In the special “long“ case, a longer reference length (e.g., 8 m) is measured at a longer distance (e.g., 8 m) from the tracker. For all other tests described above, the reference length could be relatively small, 2.25 m to 2.75 m.

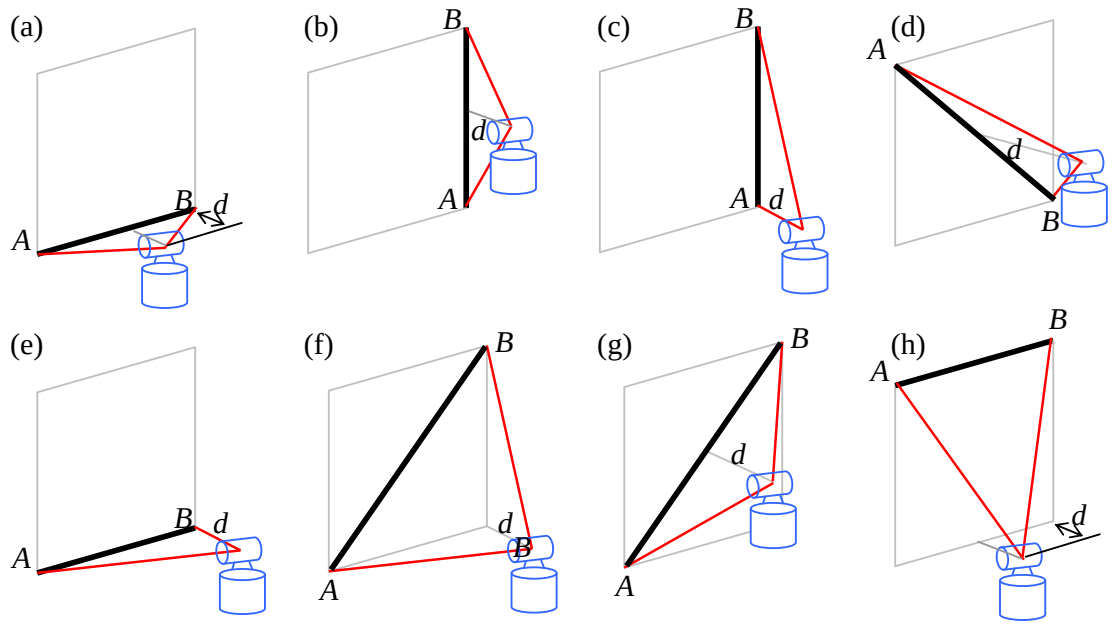

Figure 3 *(a) Symmetrically placed horizontal reference length (b) Symmetrically placed vertical reference length (c) Asymmetrically placed vertical reference length (d) Left diagonal reference length (e) Asymmetrically placed horizontal reference length (f) Asymmetrically placed diagonal reference length (g) Right diagonal reference length (g) Symmetrical horizontal reference length placed above the tracker*

5.2 Supplemental Positions: Option 1

The first default option for the supplemental positions included in the draft ISO document is mostly drawn from the ASME B89.4.19 Standard, see Table 2. Any test specified in the ASME B89.4.19 that was not included as part of the core set has been included here. In addition, some asymmetric positions that were not part of the core set are also included here. These 'mirror' positions, positions 19 to 30, are useful because some error sources produce length errors that change in sign from a nominal position to a corresponding mirror position. Thus, these tests serve as valuable diagnostic tools to detect specific tracker errors. The value of mirror positions is described in [5]. Another addition in the supplemental set are the repeatability measurements described in positions 42 to 64.

5.3 Supplemental Positions: Option 2

The second default option for the supplemental positions included in the draft ISO document is mostly drawn from the draft VDI/VDE 2617 part 10. In this alternative, the laser tracker is positioned centrically in front of the longest side of the measuring volume at a distance of 1.5 m in such a way that the measuring head is approximately equidistant from the upper and lower edge of the measuring volume. The positions are determined by eight different measurement lines as discussed in the draft. Figure 4 shows a possible arrangement of these eight measurement lines. Other arrangements are also permitted. For the remaining 64 positions, a measuring volume of 10 m x 6 m x 3 m (length x breadth x height) is recommended. If the laser tracker is used to measure small parts, a measuring volume of 5 m x 3 m x 2 m is recommended. However, other measuring volumes are permitted. In every measurement line, at least three different test lengths must be measured.

The draft ISO document recommends that 64 lengths be measured from the 8 measurement lines, and that these 64 lengths also sample the different azimuth positions of the tracker. That is, some of the 64 lengths may be measured with the tracker reading 0° when facing the measurement volume, some lengths may be measured with the tracker reading 120°, and the remaining may be measured with the tracker reading 240° when facing the measurement volume. The shortest test length should amount to at least 1/10 of the shortest side of the specified measuring volume. In each measurement line, the largest reference length has to be chosen in such a way that it is not shorter than 2/3 of the length which is maximally possible in the measurement line within the measuring volume.

Table 2 Supplemental positions

Position number	**Distance *d* from tracker**	**Description of reference length position**	**Horizontal angle(s) with respect to the tracker (°)**
1-3	3 m	Vertical, centered (i.e., the ends of the reference length are equidistant from the tracker), and the center of the length is at tracker height (see Fig. 3(b)).	90, 180, 270
4-7	6 m	Vertical, center of the length at tracker height (ends of the reference length are equidistant from the tracker) (see Fig. 3(b)).	0, 90, 180, 270
8-11	6 m	Right diagonal, centered (i.e., the ends of the reference length are equidistant from the tracker), and the center of the length is at tracker height (see Fig. 3(f)).	0, 90, 180, 270
12-15	6 m	Left diagonal, centered (i.e., the ends of the reference length are equidistant from the tracker), and the center of the length is at tracker height (see Fig. 3(d)).	0, 90, 180, 270
16-18	As close as practical	Vertical, not-centered (i.e, the tracker is directly in front of one end of the length) (see Fig. 3(c)).	90, 180, 270
19-22	As close as practical	Horizontal, not-centered (i.e, the tracker is directly in front of one end of the length), and at tracker height. This is the mirror position corresponding to positions 20-23 in Table 4 (If the tracker were previously directly in front of target *B* as in Fig. 3(e), then, the tracker must now be positioned directly in front of target *A*) (see Fig. 3(e)).	0, 90, 180, 270
23-26	As close as practical	Vertical, not-centered (i.e, the tracker is directly in front of one end of the length). This is the mirror position corresponding to positions 24 in Table 4 and positions 16-18 in this Table (If the tracker were previously directly in front of target *A* as in Fig. 3(c), then, the tracker must now be positioned directly in front of target *B*) (see Fig. 3(c)).	0, 90, 180, 270
27-30	As close as practical	Diagonal, one end is below or above the point directly in front of the tracker, the other end is at tracker height and to the right or left of the point directly in front of the tracker. The range to the two ends of the length is equal. This is the mirror position corresponding to positions 25-28 in Table 4 (If the tracker were previously directly below target *B* as in Fig. 3(f), then, the tracker must now be positioned directly above target *A*) (see Fig. 3(f)).	0, 90, 180, 270
31-33		Horizontal, centered directly above (as much as that is possible) the laser tracker itself (see Fig. 3(h)).	90, 180, 270
34-37	6 m	Body diagonal of a cube. User defined default position 2 of the B89.4.19 Standard	0, 90, 180, 270
38-41	As close as practical	Diagonal, centered (i.e., the ends of the reference length are equidistant from the tracker), and the center of the length is at tracker height.	0, 90, 180, 270

Table 2 continued: Repeatability measurements

Position number	Distance *d* from tracker	Description of reference length position	Horizontal angle(s) with respect to the tracker (°)
42-45	Distance approximately equal to half the reference length	Horizontal, centered (i.e., the ends of the reference length are equidistant from the tracker), and at tracker height. Repeat the measurement 4 times. This tests the repeatability of the horizontal angle measurement capability at the near position.	0
46-49	Distance approximately equal to twice the reference length	Horizontal, centered (i.e., the ends of the reference length are equidistant from the tracker), and at tracker height. Repeat the measurement 4 times. This tests the repeatability of the horizontal angle measurement capability at the far position.	0
50-53	Distance approximately equal to half the reference length	Vertical, center of the length at tracker height (ends of the reference length are equidistant from the tracker). Repeat the measurement 4 times. This tests the repeatability of the vertical angle measurement capability at the near position.	0
54-57	Distance approximately equal to twice the reference length	Vertical, center of the length is at tracker height (ends of the reference length are equidistant from the tracker). Repeat the measurement 4 times. This tests the repeatability of the vertical angle measurement capability at the far position.	0
58-61	3 m	Along the radial direction so that the near end of the length is 4 m away from the tracker. Repeat the measurement 4 times. This tests the repeatability of the range measurement capability.	0
62-64	6 m	Along the radial direction so that the near end of the length is 6 m away from the tracker. Repeat the measurement 3 times. This tests the repeatability of the range measurement capability.	0

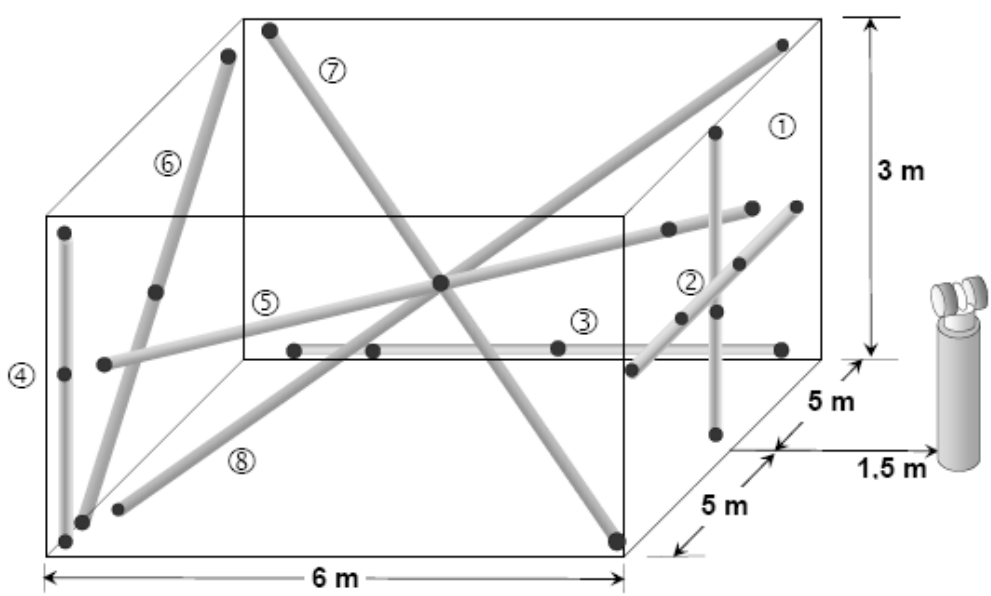

Figure 4 *Possible arrangements of the 8 measurement lines for default option 2 (source [3])*

5.4 Probe Tests and Two-face Tests

The draft ISO document includes the performance of probe size and probe form error tests, which are similar to those described in the draft VDI/VDE 2617 part 10. A sphere of calibrated diameter is measured at different locations in the measurement volume – at less than 2 m distance from the tracker, and at a distance of about 10 m or more than 75 % of its range. Twenty five data points are measured on the sphere. The SMR probe is rotated so that a different point on the SMR contacts the calibrated sphere for each measurement point. Any deviation in size and form from the calibrated values are attributed to the optical misalignments and geometry of the SMR.

The draft ISO document also requires the performance of two-face tests, which are included as probe location tests. The tests are recommended in the VDI/VDE 2617 part 10 and, are similar to those described in the ASME B89.4.19, except that the tests at the 3 m position have been removed because it is redundant.

6. Comparing the ASME B89.4.19, the draft VDI/VDE 2617 part 10, and the draft ISO 10360-10

Sensitivity to geometric errors:

As we have pointed out earlier, several length tests described in the ASME B89.4.19 are sensitive to different geometric misalignments in trackers, but there are still some redundancies and weaknesses. There is considerable symmetry in the placement of the lengths which cause reduced or no sensitivity to several geometric misalignments. The draft VDI/VDE 2617 part 10 allows considerable flexibility in the placement of the lengths and therefore it is possible to have a combination that has very limited sensitivity to different geometric misalignments. We believe that the core set of tests in the draft ISO document addresses this problem by being sensitive to known sources of geometric misalignments in trackers.

Number of tests:

The ASME B89.4.19 requires the performance of 105 length tests, 108 two-face tests, and 18 ranging tests (if there are more than one measurement devices within the tracker, there will be 18 ranging tests for each). The draft VDI/VDE 2617 part 10 requires the performance of 105 length tests, a synthetic length test, and three probe tests which involve measurement of a sphere of known diameter and form (if more than one probe (SMR) is used, the probe tests have to be performed for each probe). The draft also recommends 18 two-face interim tests that may periodically be performed on the tracker. The draft ISO document contains 105 length tests (including the synthetic length test and ranging tests), 18 probe location tests (two-face tests), and two probe size tests.

Similarity to the ISO 10360-2:

The ASME B89.4.19 Standard is similar to the ISO 10360-2 in its testing philosophy in that calibrated artifacts are employed along the principal directions to capture specific sources of error. In ISO 10360-2, calibrated lengths are placed along the three principal directions *x*, *y*, and *z*, and along diagonals to capture errors associated with the motion of a single axis or combination of axes. For a laser tracker, the three principal axes are the ranging axis and the two angular axes. The ranging tests in the B89.4.19 capture errors along the ranging axis. Errors associated with the two angular axes, or combination of all three axes, are measured by placing calibrated lengths along the different directions. For example, the horizontal length test captures errors associated with the horizontal angle axis of the tracker. A

diagonal length test captures the squareness between the two angular axes. These ideas are illustrated in Fig. 5. Fig. 5 (a) shows some testing positions according to the ISO 10360-2 with the artifact aligned along the *x* axis, the *y* axis, the *z* axis, and along a space diagonal. Fig. 5 (b) shows some testing positions according to the ASME B89.4.19 with calibrated lengths along the ranging axis, along the horizontal and vertical directions to test the two angular axes, and along a diagonal to test for squareness.

The draft VDI/VDE 2617 part 10 is similar to the ISO 10360-2 Standard in its approach to specifying the limiting values of the errors. The ISO 10360-2 allows the limiting value of the length measurement error to be a single quantity (a constant) or a simple formula (of the form *A+BL*) and must be complied for any length over the entire volume. The ASME B89.4.19 on the other hand allows manufacturers to provide any formula of their choosing to determine the limiting value of the length measurement error; common formulas provided by manufacturers are indeed elaborate. The draft VDI/VDE 2617 part 10 adopts the ISO 10360-2 approach by allowing either a single quantity or a simple *A+BL* type formula for this purpose.

The core set of the draft ISO document is similar to the ISO 10360-2 in that errors in each axis are tested by careful positioning of the reference lengths to achieve maximum sensitivity. The limiting values of the errors will be a formula; whether they will be a simple formula of the type *A+BL* or a more complicated one is still under discussion.

7. Conclusions

Both the ASME B89.4.19 and the draft VDI/VDE 2617 part 10 provide some excellent tests for the performance evaluation of laser trackers. But, as pointed out, there are some limitations as well. The symmetrical positioning of the lengths in the ASME B89.4.19 and the

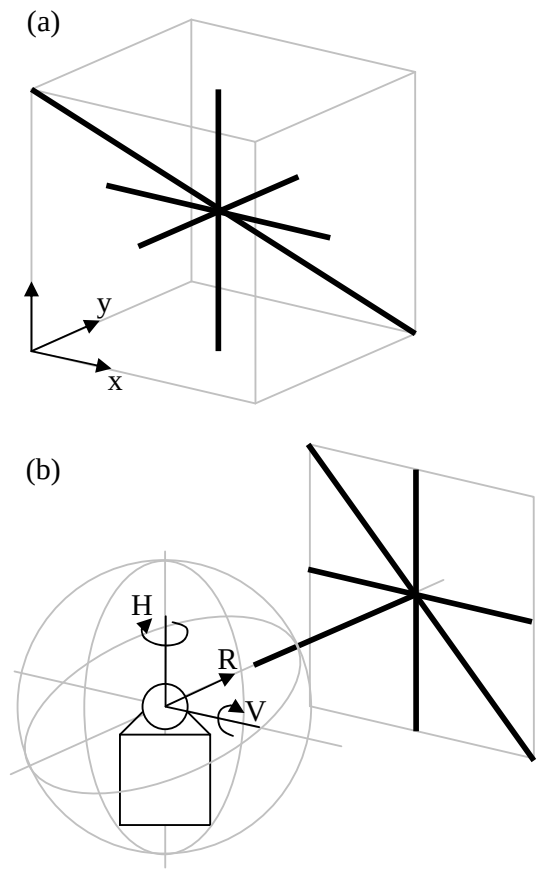

Figure 5 *(a) Some testing positions according to the ISO 10360-2 (b) some testing positions according to the ASME B89.4.19*

flexibility in the positioning of the lengths in the draft VDI/VDE 2617 part 10 result in reduced or poor sensitivity to different geometric misalignments in trackers. The ISO draft document addresses these concerns by introducing considerable asymmetry in the positioning of the lengths and introducing both a core set of fixed positions and a supplemental set of user-defined flexible positions. The draft ISO document also has the inclusion of the two-face tests because they are simple, quick and highly efficient way of detecting tracker error sources. Additionally, the draft ISO document includes probe (SMR)

tests that are similar to the VDI/VDE 2617 part 10 testing procedure.

A test that is currently not included in the draft ISO document but may be considered is the repeated measurement of a horizontally oriented length, but with the tracker rotated about the azimuth by a small amount (say, 0.003°) between measurements. The purpose of this test is to detect uncompensated high frequency periodic errors in the horizontal angle encoder. Two other aspects not yet addressed in the ISO document are the inclusion of any dynamic tests as described in the Chinese draft Standard [10] and interim tests such as a bundle adjust procedure [11]. Both are excellent tests and worthy of consideration.

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