EVALUATION OF THE RANGE PERFORMANCE OF LASER SCANNERS USING NON-PLANAR TARGETS

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INTRODUCTION

The Dimensional Metrology Group (DMG) at the National Institute of Standards and Technology (NIST) is involved in the development of documentary standards for volumetric performance evaluation of laser scanners.

The proposed tests evaluate the performance of laser scanners by determining the measurement error between two derived points[§] at many positions in its work volume. Some of the proposed test positions are along the ranging direction of the laser scanner. Considerable work was done by the ASTM E57.02 committee on "Test methods", however targets specified by the ASTM E2938 [1] standard are limited to planar targets.

This paper explores non-planar target artifacts such as spherical and trihedral targets, primarily to understand the influence of target geometry on ranging errors.

TARGET SELECTION

Flat planar targets are convenient to use in evaluating the relative range error. These targets are easy to fabricate or obtain commercially. They yield a measurand whose length value is dependent on its angle/orientation, processing method, density and distribution of data collected on the target.

A sphere's derived point is its center and can be calculated with lower uncertainty by using a least-squares minimizing algorithm. For larger distances, larger diameter spheres are needed to capture enough data points on its surface. Since the sphericity (form) of the target sphere affects the determination of its center [2], obtaining commercially manufactured spheres of larger diameters and good sphericity is cost prohibitive. Spheres measured using laser scanners also suffer from the issue of having increased measurement noise towards the outer periphery of the sphere surface.

Contrast targets used by some laser scanner manufacturers employ proprietary methods to calculate the derived point on the target and hence are difficult to evaluate independently. Further, this derived-point calculation may not use the 3D point coordinates directly, but may use an indirect correspondence between the intensity data and the 3D coordinates.

In some proposed test positions for the volumetric evaluation, the targets may be located asymmetrically (not equidistant from the scanner). In such cases, the derived points calculated from the scans suffer from the problem of unequal range noise and uncertainty for all the four target geometries mentioned in this paper.

MEASUREMENT NOISE VS INCIDENCE ANGLE

A test was conducted to understand the effect of angle of incidence on the range noise of a laser scanner. This test consisted of mounting a flat aluminum plate on an adjustable stage and scanning multiple times at different angles.

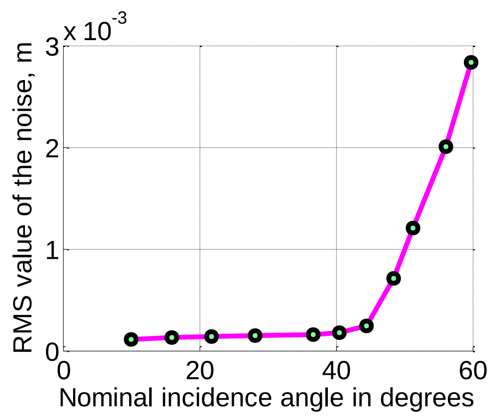

Figure 1. Noise vs incidence angle

§ A derived point is a uniquely identifiable point on a target that is dependent on its geometry. Examples include sphere center, apex of a pyramid etc.

By fitting a plane to the scan data, the RMS (root-mean-square) values of the residuals (noise) were calculated. It was observed that the noise increases exponentially as the angle of incidence increases beyond 45º.

Figure 1 shows the results of this test. It should be noted that, the instrument manufacturer specifies a value of 50º as the angle beyond which the measurement signal deteriorates resulting in higher noise.

TESTS TO COMPARE RANGE USING TARGETS OF VARYING GEOMETRY

A series of four tests were performed to understand the effect of target geometry on the relative range error (E_{RR}). Each of the four tests varies in either the target geometry, or the procedure to calculate the reference/test length. The setup consists of two locations for the target on a sturdy tripod – a near position and a far position. The reference instrument (RI) was a laser tracker and the instrument under test (IUT) was a laser scanner. The four targets used in these tests were as follows:

a) Flat plane target
b) Trihedral target
c) Hollow sphere target
d) Integrating sphere target

For all targets except the integrating sphere target, the RI, IUT and the tripod positions were as illustrated in Figure 2. These three targets were tested simultaneously. For the fourth target (integrating sphere), the RI and IUT were on either side of the target as illustrated in Figure 3.

Of the two positions, the near position was at about 3 m away from IUT and the far position was about 8 m away from the near position, along the line joining IUT and the near position.

To reduce any errors due to the angular encoders, the RI and IUT need to be mounted on the same tripod in succession for taking the reference and IUT measurements. However, that was not the case in the setup described in Figure 2. This setup introduces an error of about 0.03 mm (1σ) in the reference length due to the angular encoder errors which was considerably smaller than the relative range errors.

In all the tests, four derived points were obtained - two at the near position and two at the far position. At the near position, the first derived point was obtained using the RI, and the second derived point was obtained using the IUT. The target was then moved to the far position and two more derived points were obtained similarly using the RI and IUT. Reasonable care was taken to make sure that the angle/orientation of the targets does not significantly change (with respect to the IUT). This was accomplished by marking the footprints of the tripod on the floor at both the positions and placing them back at approximately the same location during repeat measurements.

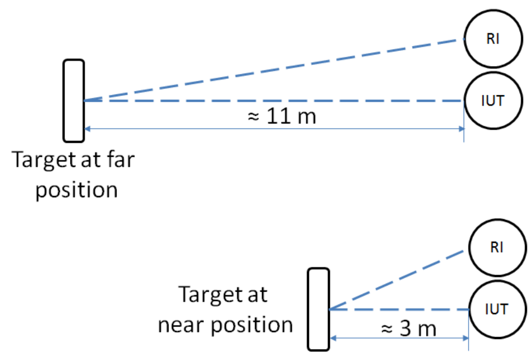

Figure 2. Location of RI, IUT and the two locations of 3 targets in Figure 4.

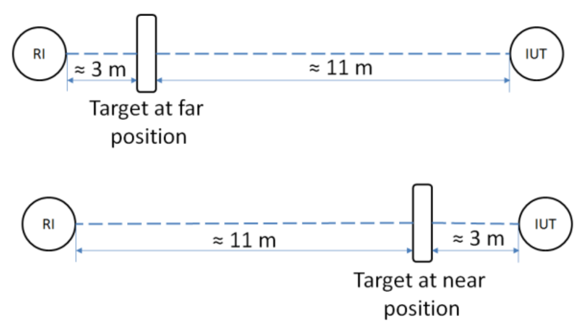

Figure 3. Location of RI, IUT and the two locations of the Integrating sphere target.

The reference length (L_{RI}) was the Euclidean distance between the derived points obtained using the RI at the near and the far positions. The test/IUT length (L_{IUT}) was the Euclidean distance between the derived points obtained using the IUT at the near and the far positions. The relative range error (E_{RR}) was calculated using equation 1.

$$E_{RR} = L_{IUT} - L_{RI} \quad (1)$$

In the next few sub-sections, the various target geometries are described and methods to obtain

L_{IUT} and L_{RI} are explained. These values were then used to calculate E_{RR}, using equation 1.

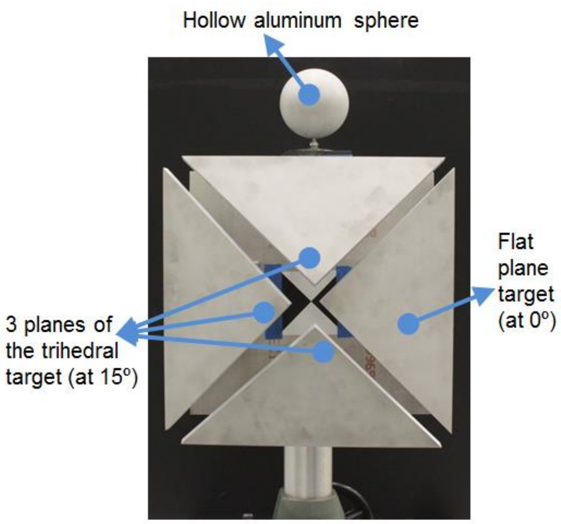

Figure 4. Picture of the trihedral, flat and hollow aluminum sphere targets mounted on a tripod

Flat plane target:

The flat plane target was constructed from a triangular aluminum plate as depicted in Figure 4. Its surface was bead blasted to make its surface diffusely reflecting for the laser scanner. The derived point was the centroid of this plane. This target was mounted on to the tripod and placed at the near position and the far position successively and was measured using the RI and IUT to calculate the relative range error E_{RR}.

Calculating L_{RI}: To obtain the two derived points for the reference length using the RI, seven points were measured on the flat plate at both the positions (near and far) using the SMR (surface mounted retroreflector) walking method [2]. Three points were collected close to the vertices of the triangle, three points at the mid points of the sides and one point at the center of the triangular plate. The Euclidean distance between the two derived points (centroids) at the near and far positions will yield an L_{RI} value. A repeatability test was conducted to estimate the variation in the reference length in the ranging direction and the 1σ variation of 10 measurements was 0.165 mm.

Calculating L_{IUT}: The test length (L_{IUT}) was calculated by using the following procedure:

a) First the scan data was segmented to obtain the data corresponding to the flat plate.
b) Then the edge points were eliminated. This was performed by considering a cylindrical region whose axis passes through an initial centroid of the scan data and was along the ranging direction. The radius of this cylindrical region was empirically determined to exclude the edge points. All the points within this cylindrical region were considered for further processing.
c) A plane fit was performed on the data obtained in step #b) and the residuals were obtained. Points corresponding to the residuals exceeding two times the standard deviation (2σ) value were excluded from this data.
d) A centroid was calculated for the data obtained in step #c) and this was the derived point for the flat plane.
e) Another derived point was obtained at the far position and the Euclidean distance between the two derived points was the test length (L_{IUT}).

Note that this procedure for the flat plane target does not adhere to the procedure described in the ASTM E2938 [1] standard.

Trihedral target:

Three aluminum flat triangular plates similar to the flat plane target were used to form a trihedral target and are depicted in Figure 4. The derived point for this target was the intersection of the three planes. This target was first mounted on to the tripod. It was then measured using the RI and IUT while placed at the near position and then at the far position to calculate the relative range error E_{RR}. The three planes of the trihedral target were oriented in such a way that the incident angle of the laser beam from the IUT was ≈15º.

Calculating L_{RI}: To obtain the two derived points for the reference lengths using the RI, the three planes were measured using the method similar to that for the flat plate. Seven points were measured on each of the three surfaces of the target and three planes were fitted to these three sets of data. The intersection of these three planes was the derived point of the trihedral target. The Euclidean distance between the two derived points at the near and far positions will yield L_{RI}. A repeatability test was conducted to estimate the variation in the reference length in the ranging direction and the 1σ variation of 10 measurements was 10 µm.

Calculating L_{IUT}: To obtain the derived point using the IUT, the data on each of the three planes was processed using the steps a), b), and c) described for the flat-plane target. Three planes were then fit to these three sets of data and the intersection of these three planes was the derived point for the trihedral target. Similarly, the second derived point was calculated at the far position and the test length (L_{IUT}) was calculated.

Hollow spherical target:

A bead blasted hollow aluminum sphere (101.6 mm in diameter) was mounted on the tripod as depicted in Figure 4. The derived point for this target was the sphere center.

Calculating L_{RI}: The two derived points for the reference length were the two sphere centers calculated by using the SMR walking method [2]. A set of ≈15 points were measured on the sphere surfaces at both the positions using the RI. The sphere centers were then calculated by fitting a sphere using a constrained non-linear least squares algorithm. The Euclidean distance between the two sphere centers at the near and far positions will yield L_{RI}. A repeatability test was conducted to estimate the variation in the reference length in the ranging direction and the 1σ variation of 10 measurements was 0.010 mm.

Calculating L_{IUT}: The two derived points for calculating the test length (L_{IUT}) were obtained by first scanning the spheres at both the positions (near and far) using the IUT. The scan data was segmented to extract the sphere region and was then fitted using a constrained non-linear least squares algorithm.

Integrating sphere target:

A commercial sphere called the “Integrating sphere” was used in this test. This is a truncated sphere (100 mm in diameter) that has a pocket milled into the truncated portion of the sphere. Centered at the bottom of this pocket is a kinematic seat for a 1.5 in. diameter (38.1 mm) SMR/sphere. The concentricity of a 1.5 in. (38.1 mm) diameter sphere and the Integrating sphere, as measured by a coordinate measuring machine (CMM) was <10 µm. The derived point for this target was the sphere center.

Calculating L_{RI}: The two derived points for the reference lengths were an average of 20 points as measured by the RI using an SMR when it was seated in the integrating sphere’s kinematic seat. A set of 10 points were obtained from the RI before the IUT measurement scan and 10 points after the scan. A repeatability test was conducted to estimate the variation in the reference length in the ranging direction and the 1σ variation of 10 measurements was 0.005 mm.

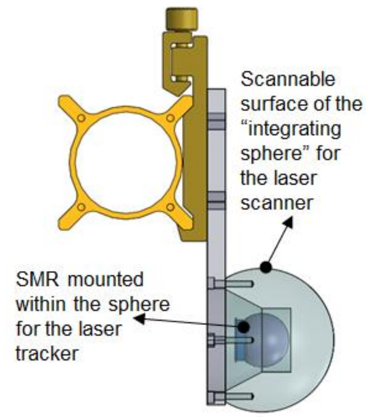

Figure 5. Illustration of the top view of integrating sphere mounted for measurement by the IUT and RI

Calculating L_{IUT}: The two derived points for calculating the test length (L_{IUT}) were obtained by a process similar to that for the hollow sphere. The sphere was scanned at both the positions (near and far) using the IUT. The scan data was then segmented to extract the sphere region and the data was fitted using a constrained non-linear least squares algorithm.

RESULTS AND DISCUSSION

For each of the four targets, eight values of relative range error (E_{RR}) were obtained. Figure 6 shows a plot of the relative range errors for various target geometries and Table 1 shows the corresponding statistics for each target.

A few observations can be made from these results:

- The two spherical targets have the lowest variation (1σ) in the relative range error (E_{RR}) compared to the other targets.
- The flat plane target has the largest variation (1σ) of E_{RR}.
- The E_{RR} values for both the spheres were statistically similar.
- The trihedral target has the lowest absolute mean value of E_{RR}, but has

slightly higher 1σ variation than the spheres.

- The flat plane target has the largest absolute mean value of E_{RR} apart from the largest 1σ variation of E_{RR}. An explanation for a possible reason for such a large bias will be provided later in this section.
- The flat plane targets measure shorter than their reference lengths, whereas the spherical targets measure longer than their reference lengths.

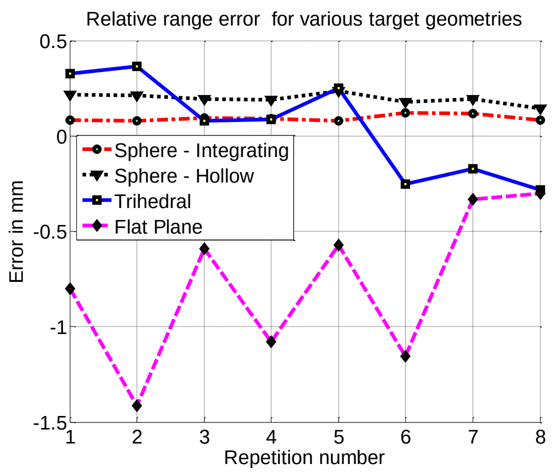

Figure 6. Plot showing the relative range errors for various geometries

Table 1. Statistics for the relative range error tests on four targets

Target type	Nom. length (L_{NOM})	1σ of L_{RI} (mm)	Mean of E_{RR} (mm)	1σ of E_{RR} (mm)
Sphere-I**	7.8 m	0.005	0.094	0.017
Sphere-H**	8.4 m	0.010	0.195	0.028
Trihedral	8.4 m	0.010	0.051	0.259
Flat plane	8.4 m	0.165	-0.781	0.403

Flat plane targets using the centroid as a derived point resulted in relative range errors that were larger compared to other targets used in these tests. The measurement of the derived-point to derived-point lengths for data from both the instruments relies on the target plates to be perfectly parallel.

For two perfectly parallel planes, if the centroids determined by RI and IUT are not identical, then the error is negligible as this error is not in the ranging/sensitive direction (cosine/second order error). However, if the planes are not parallel, an error in the centroid determination will result an error in the sensitive direction (first order error). This was exacerbated by the fact that the reference length was calculated based on a centroid determined by only seven points at each position.

As an example, consider two flat plane targets at the near position and the far position that are not parallel and are at 1° with respect to each other. Also consider that there is a 5 mm error in locating the centroid in the plane perpendicular to the sensitive direction. Such a setup will result in an error of 87 µm error in the relative range.

We plan to perform more tests using the flat plane target by making sure that the targets at the near and far positions are truly parallel and using alternative processing methods. The parallelism might be achieved by designing a kinematic mounting setup that uses a plane mirror and a laser for alignment.

One alternative processing method is to fit the data from the near and far locations using a parallel plane fitting algorithm [3] and calculating the distance between the fitted parallel planes. This method can still suffer from a first order effect with respect to the parallelism of the planes. Other methods to try include a bounding box method and the intersection of diagonals [1].

CONCLUSION

Four targets were tested for measuring relative range error of a laser scanner. Of these, one used a flat plane target. The flat plane target, where the centroid was the derived-point for the reference length results in larger relative range errors compared to the other three targets.

In contrast, spheres and trihedral targets have lower relative range errors and are less sensitive to their angle/orientation with respect to RI and IUT.

These tests indicate that the target geometry, alignment and the processing method affect the relative range error. More tests are planned (various lengths and processing methods) to understand the effect of target geometry on the relative range error.

** Sphere-H is the hollow sphere and Sphere-I is the integrating sphere

REFERENCES

[1] ASTM E2938 standard: "Test method to evaluate the relative-range measurement performance of 3D imaging systems in the medium range"

[2] Rachakonda, P., Muralikrishnan, B., Lee, V., Sawyer, D., Phillips, S., Palmateer, J., "A Method of Determining Sphere Center to Center Distance Using Laser Trackers For Evaluating Laser Scanners", Proceedings of the American Society for Precision Engineering, Annual Conference, Boston, Massachusetts, November 09-14, 2014.

[3] Shakarji, C., Srinivasan, V., "Theory and algorithms for weighted total least-squares fitting of lines, planes, and parallel planes to support tolerancing standards", Journal of Computing and Information Science in Engineering,13(3)