TARGETS FOR RELATIVE RANGE ERROR MEASUREMENT OF 3D IMAGING SYSTEMS

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1 INTRODUCTION

The Dimensional Metrology Group (DMG) at the National Institute of Standards and Technology (NIST) is performing research to support the development of documentary standards within ASTM E57 [1] for the point-to-point performance evaluation of 3D imaging systems that use a spherical coordinate system.

The currently proposed tests call for the evaluation of point-to-point performance of these systems by determining the measurement error between two derived points* at a number of positions in the instrument's work volume. A part of the proposed standard involves measurements along the ranging/radial direction of the instrument and investigations were carried out at NIST to understand the suitability of various targets for this aspect of the standard. This paper will only discuss the variety of artifacts that were considered and investigated for use in these ranging test positions. The other aspects of the point-to-point tests are covered in another report [2].

2 OVERVIEW OF STANDARDS ACTIVITIES

The ASTM E57.02 sub-committee on "Test Methods" started work in 2007 to standardize test methods to evaluate the performance of 3D imaging systems. The first test that the sub-committee decided to develop was the relative range test because the ability to measure range was fundamental to these systems. The work concluded in 2013 and a relative range standard was published in 2015 (ASTM E2938 [3]).

In 2013, the sub-committee started to work on an expanded scope to evaluate the point-to-point performance of these instruments. The sub-committee meets every two weeks over a WebEx† teleconference to present the technical work and discuss the proposed standard.

The initial draft of this point-to-point performance standard has 12 two-face tests and 35 point-to-point tests, repeated three times. Two-face tests involve the measurement of a single stationary target using the front face and again using the back face of the instrument under test (IUT) [4].

* A derived point is a unique point obtained from a group of measured points on an artifact and is not a measured point. It is dependent on the artifact geometry. Examples include a sphere center obtained by fitting a sphere to points measured on the sphere's surface; the apex of a pyramid obtained by the intersection of three or more planes by measuring the planar surfaces of the pyramid.

† Disclaimer: Commercial equipment and materials may be identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

The distance between the derived points obtained from the front face and back face is itself the error; no reference length measurements are required for these tests.

Point-to-point tests involve measuring the distance between two targets using a reference instrument (RI), then with the IUT and comparing them. The draft standard on point-to-point performance includes point-to-point tests in both the radial and non-radial directions. Of these 35 tests, three tests are along the ranging/radial direction.

By the end of 2015, a test facility for implementing the point-to-point tests was established at NIST and in May 2016, a run-off meeting was held to allow manufacturers to evaluate all of the tests in the draft standard. Five manufacturers participated in this meeting, performed all the tests and provided feedback to improve the standard.

A significant topic that was debated prior to and during the run-off meeting was the choice of target geometry for the three ranging direction tests. The sub-committee agreed that a target with spherical geometry would be used for all two-face tests and all point-to-point length tests that are not along the radial direction. However, it was not clear if spheres would be suitable for long ranging/radial length tests. In this context, the DMG at NIST investigated various artifact geometries to determine their relative merits as targets for the ranging/radial length tests.

The next sections will discuss the targets that were considered and the objective criteria to evaluate each of them.

3 OVERVIEW OF RELATIVE RANGE TESTS

A relative range test is performed by placing the target at two positions (a near position and a far position), measuring the target at both positions with the IUT and the RI and calculating the relative range error. If L_{IUT} and L_{RI} are the distances between the near and far locations of the targets as measured by the IUT and RI respectively, then the relative range error (E_{RR}) is given by: $E_{RR} = L_{IUT} - L_{RI}$. The RI in all the tests performed at NIST is a laser tracker and the IUT is a laser scanner, however the choice of instrument for RI is left to the user.

Depending on the design of the target, the relative range tests can be performed in one of two configurations. In the first configuration, both the RI and IUT are on the same side of the target (Figure 1) and in the second configuration, they are on the opposite side of the target (Figure 2). Alternative configurations were proposed and discussed by the sub-committee, but these two configurations offered lower uncertainties in obtaining the reference lengths.

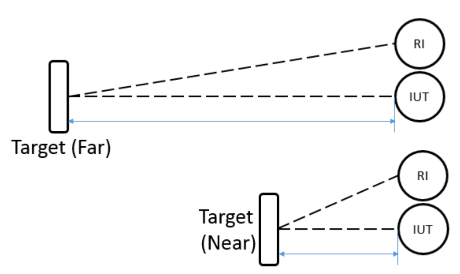

Figure 1: Relative range test with RI and IUT on the same side of the target.

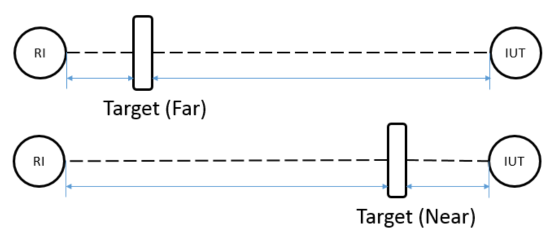

Figure 2: Relative range test with RI and IUT on either side of the target.

The choice of the configuration depends on the procedure to obtain the derived point using the RI. It should be noted that, the configuration in Figure 1 yields a slightly greater uncertainty in determining the reference lengths as the RI is not in-line with the target positions. In such a configuration, errors associated with the angular encoders increase the reference length uncertainty. Even though the configuration in Figure 2 offers lower uncertainty (than the first configuration), it results in higher uncertainty for shorter lengths and lower uncertainty for longer lengths. This may be problematic as the IUT will likely have tighter specifications for shorter lengths and wider specifications for longer lengths.

The published ASTM E2938 [3] standard mandates the use of plane targets. Since the work on this standard concluded in 2013, new targets started becoming commercially available that offer more efficient ways to realize these tests. The pros and cons of each of these targets will be discussed in the subsequent sections.

4 CHARACTERISTICS OF AN IDEAL TARGET

To objectively evaluate the benefits of various targets, some of the following characteristics were considered:

1. The IUT has to be able to measure the targets at all the test distances‡ (1 m to 60 m), with respect to size and reflectivity and result in reliable data to calculate a derived point.
2. Measurement of the reference distance should be as simple/convenient as possible and practical in order to reduce measurement time.
3. The derived point needs to be obtained from dimensional data only (instead of intensity images etc.)
4. The RI and IUT have to measure the same point on the target so as to permit comparison of the measured lengths.
5. The target should be able to be aligned and mounted in a manner which minimizes the reference length uncertainty (U_{RL}) and results in U_{RL} that is a suitable fraction of the IUT specification limit.
6. The measurement procedure should limit the physical touching of the target or the mounting apparatus to prevent introduction of additional errors.
7. The target influences (such as geometry, surface finish, texture, color, lack of symmetry etc.) on the measurement should be as small as practically possible.
8. The procedure to obtain the derived point should be sufficiently repeatable over the entire testing range.
9. The target has to be relatively inexpensive to fabricate.

Five target types were considered for the purpose of evaluating the relative range of 3D imaging systems, namely a) Planes, b) Contrast targets, c) Spheres, d) Pyramids and e) Hybrid targets. They will be discussed in the subsequent sub-sections:

4.1 Planes

Planar targets have geometries that are simple and introduce insignificant geometry dependent errors that vary with range. The plane targets that are considered for use with laser scanners are metal

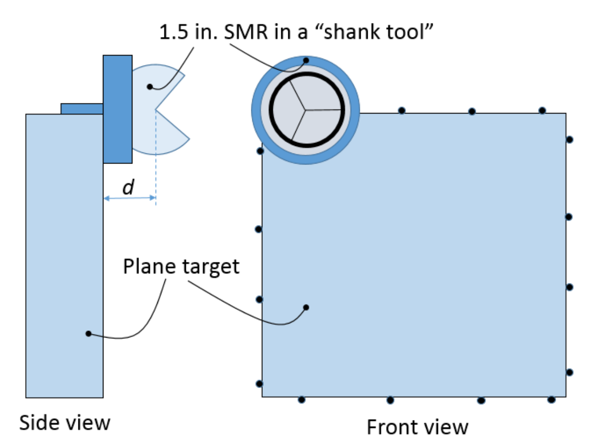

Figure 3: An illustration of the measurement process to obtain the derived point of a plane target using a reference instrument.

‡ The proposed tests are for IUT with a maximum range of 150 m. However, the long range facility at NIST is 60 m long and the artifacts can be reliably tested only within 60 m range. The instrument range may go beyond 60 m (Typically 100 m to 300 m)

(usually aluminum) that have been vapor/media blasted, resulting in a lambertian surface with diffuse reflectivity. Such surfaces result in data that has relatively low noise (when compared to shiny or dark surfaces) and a return signal that is of uniform intensity over its entire surface. The target specifications (flatness, finish etc.) are simple enough for most machine shops to fabricate them with relative ease.

The ASTM E2938 [3] standard allows a variety of methods to calculate the reference and test lengths between two target positions. One method to obtain the derived point of a square plane target is to use a "shank tool", a spherically mounted retroreflector (SMR) and a laser tracker as an RI. A "shank tool" is a special commercial mount for an SMR that allows it to be positioned over an edge of the target to measure points that are offset from the plane. The two planes at the edge need to be nearly orthogonal to each other for an effective use of the "shank tool". The procedure to obtain the derived point is described below and is illustrated in Figure 3.

1. An SMR mounted on a "shank tool" in conjunction with a laser tracker is used to collect 4 sets of data on a plane target (one set per edge). Each set consists of four points resulting in a total of 16 points. More points can be recorded and processed if needed.
2. A 3D line is fitted to each set of points corresponding to each of the four offset edges yielding four 3D line equations.
3. Points corresponding to the four corners are calculated by intersecting the four pairs of two adjacent 3D lines. Because two 3D lines may not intersect at all, the point of intersection of two 3D lines is the point in space which is the closest point to both of the lines, determined in a least-squares sense.
4. The average of these four intersection points is the centroid of an offset surface from the plane target. The offset distance '*d'* is equal to the distance from the base of the "shank tool" to the center of the SMR mounted in it (as illustrated in Figure 3).
5. A plane is then fit to the 16 points obtained in step #1. This is a plane that is offset from the target surface by the same distance '*d'* towards the IUT.
6. Another plane is constructed that is parallel to the offset plane (obtained in step #5) and is at a nominal distance *'d'* away from the IUT.
7. The centroid obtained in step #4 is then projected on to the plane constructed in step #6.
8. This projected point is the derived point for the plane target.

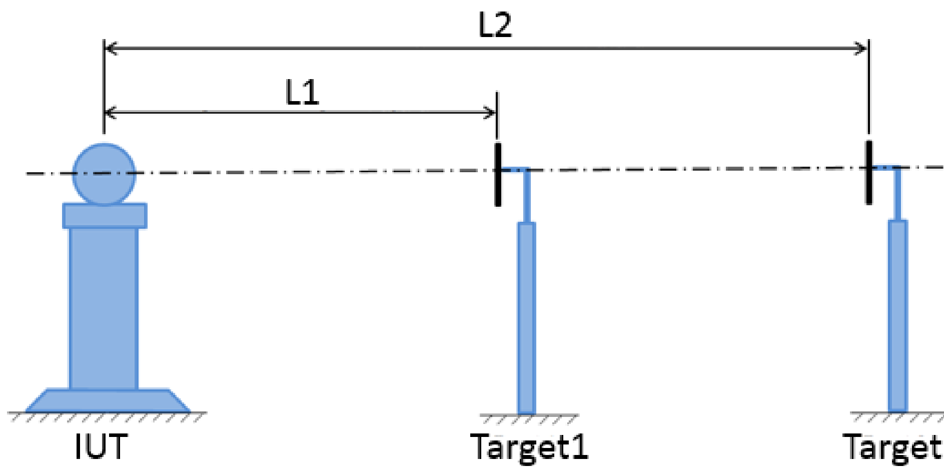

Figure 4: Relative range test with planes placed at two locations in-line with each other and the IUT (laser scanner)

To determine the centroid of the plane from the scan data, the following procedure is required by ASTM E2938 [3] standard.

1. Eliminate from the IUT data set all measured points that are part of the background, surroundings, and plane target supports.
2. Select measured points that will be used for the plane fit by omitting the measured points that are in the edge exclusion regions.
3. Fit a least-squares plane and calculate the standard deviations of the residuals.
4. Eliminate measured points on the plane targets for which the magnitude of the residuals is greater than twice the standard deviation of the residuals of the plane fit.
5. Determine the geometric center of the plane target using 2D or 3D methods.

To minimize the relative range errors, these targets need to be aligned perpendicular to the line joining the target positions and IUT (Figure 4). Any misalignment will result in Abbe errors that alter the relative range errors. For example, if the error in determining the geometric center of the plane (from IUT data) is 3 mm and if there is a 5° error in aligning the target with respect to the line joining the IUT and two target positions, this will result in 0.26 mm error in the ranging direction.

4.2 Spheres

Spheres are popular targets among users of 3D imaging systems (like laser scanners) as their geometry is the same in all the directions. This property is helpful when registering or aligning scans obtained from various positions. The derived point of a sphere target is its center and calculating a sphere center can be accomplished by a variety of established algorithms.

Three sphere targets were evaluated for relative range tests. They are a) Hollow - Painted plastic spheres, b) Hollow - Custom aluminum spheres, c) Special "integration spheres". Each of these targets will be discussed in the following sections.

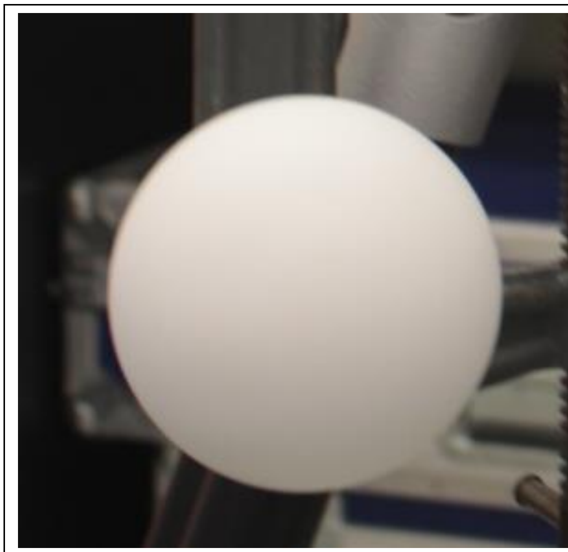

Figure 5: Hollow spheres – Painted plastic laser scanner sphere

4.2.1 Hollow – Painted plastic spheres

These are hollow plastic spheres that are typically painted with a white and diffuse coating and are mounted on a stem. These are commercially available from a variety of vendors. Due to the white paint used on these spheres, these spheres are visible to the 3D imaging systems from large distances.

These targets however are light, fragile and are not dimensionally stable. The form (sphericity[§]) on these spheres is also poor and is in the range of 0.3 mm to 2.0 mm, which results in an unacceptably large reference length uncertainty. These characteristics of the plastic spheres also make the determination of a reference length (with acceptable level of uncertainty) very challenging.

[§] In this publication, sphericity is defined as the smallest separation of two concentric spheres that contain all the points of the surface under consideration.

4.2.2 Hollow – Custom aluminum spheres

These are custom aluminum spheres (mounted on a stem) that are media blasted to provide a dull finish that is nearly lambertian. The form (sphericity) on these spheres is typically less than 0.02 mm on a 100 mm diameter sphere (by design). These are dimensionally stable artifacts that allow in-situ measurement using a laser tracker and an SMR to obtain the derived point (and thereby a reference length).

Though dimensionally stable, these spheres are less reflective than the painted spheres and do not scan as well at longer distances (compared to a similarly sized white painted sphere). Also, due to the fact that these are custom made spheres, they are more expensive and are not as readily available commercially as the painted spheres.

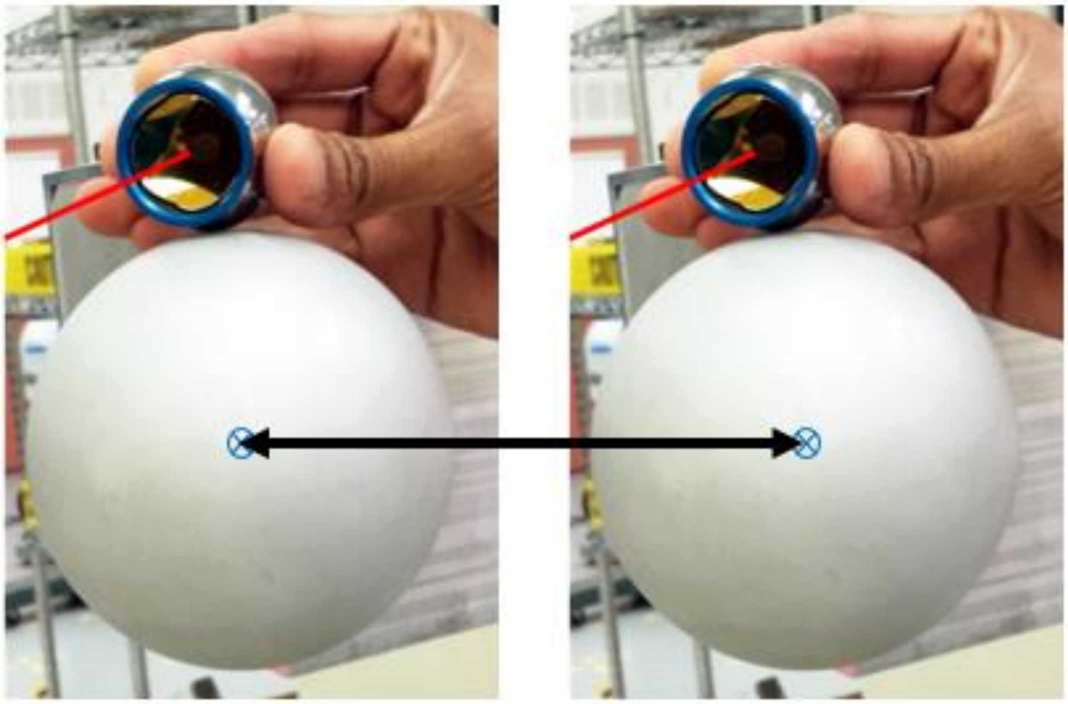

Figure 6: SMR walking method to obtain the reference length between two spheres.

To obtain the reference derived point of the sphere (sphere center), an SMR walking method [5] is used. Several points (typically more than 25) are obtained by probing the sphere surface using an SMR. The sphere center is determined by fitting these points using a non-linear least squares algorithm that constrains the radius of the sphere to its calibrated value (known a priori by measuring it on a touch probe CMM[**]). The second sphere is measured and the derived point is calculated using the same method. The distance between the two sphere centers is the reference distance for that particular test.

4.2.3 Integration spheres

These are commercial aluminum spheres that have a kinematic nest (with a magnetic preload) near their centers for a 1.5 in. diameter (38.1 mm) sphere or a 1.5 in. SMR. The kinematic nest is constructed in such a way that the center of a 1.5 in. diameter sphere (located in the kinematic nest) is concentric with the center of the outer sphere to within 0.01 mm. The form (sphericity) on these integration spheres is also within 0.01 mm and the outer surface has a near

[**] Coordinate measuring machine

lambertian finish. Custom modifications were done to add mounting holes on its outer periphery to mount it on a flat plate (as depicted on the right side in Figure 7).

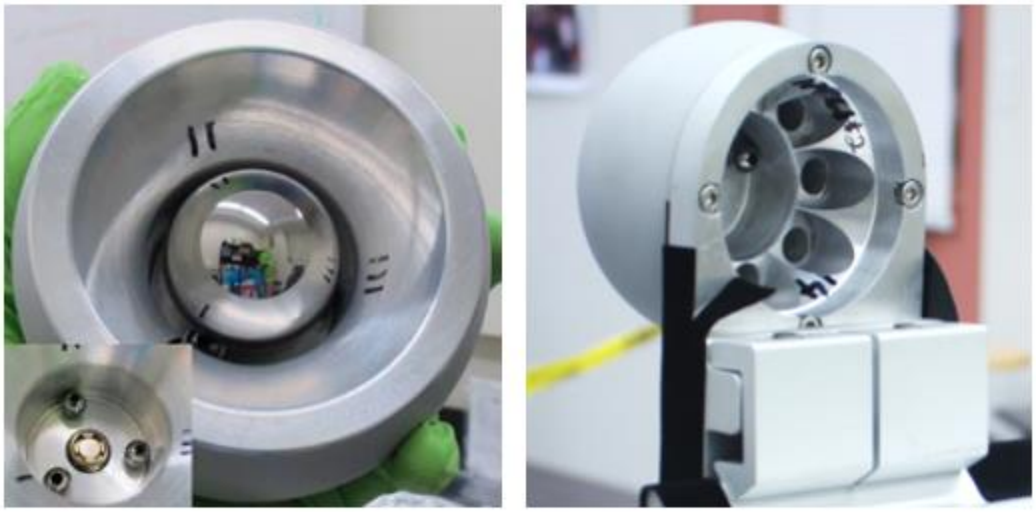

Figure 7: Two designs of a commercial “integration sphere”

To measure the reference distance between spheres at two locations, a single point measurement using a reference instrument is sufficient at each position. This process does not involve any touching of the target and minimizes any mounting related errors. This design allows the possibility of automating the reference length measurement and also techniques that could lower the reference length uncertainty [2].

4.2.4 Point cloud data considerations for spheres

Spheres, although suitable for the reasons discussed in the previous sections, have a few shortcomings with respect to data quality and reliability of the derived point obtained from such data. Some of these are discussed in the next few sub-sections.

4.2.4.1 Coverage

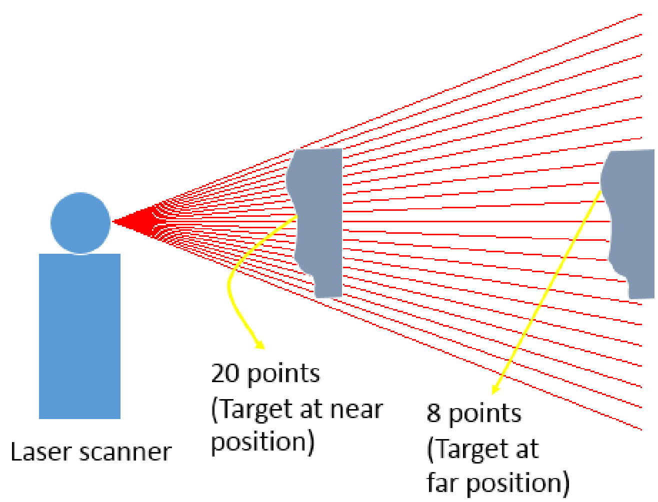

Figure 8: Point density variation from near to far position

For a given instrument setting, the number of points on a target that is farther from the IUT is less than that for a target that is closer to the IUT (as illustrated in Figure 8). For a sphere target, this issue is exacerbated by the fact that the return intensity is not the same from all the locations on its surface. Return beam corresponding to lower return signal intensity may not register with the instrument, resulting in missing points from a sphere’s outer periphery (compared with data from the sphere’s surface at the center). This reduces the “coverage area” of the scan data on a sphere at the farther location, compared with that at the nearer location (as illustrated in Figure 9). This in turn increases the error when calculating the center of the sphere using a non-linear least-squares fitting algorithm.

4.2.4.2 Squishing and Flaring of spheres

For some instruments, the quality of the scan data from the sphere surface varies over its surface from its center to the outer periphery. There are a number of hypotheses as to why this effect is observed: varying slope, beam width, multi-path effects due to the mounting apparatus or a variety of other instrument related error sources. Because of this, when the data from such targets is fit to a sphere using a non-linear least-squares algorithm without constraining the radius, the resulting radius (R_{UNC}) is different from its calibrated radius (R_{CAL}). As a result, the spheres may appear "squished" ($R_{UNC} < R_{CAL}$) or flared ($R_{UNC} > R_{CAL}$).

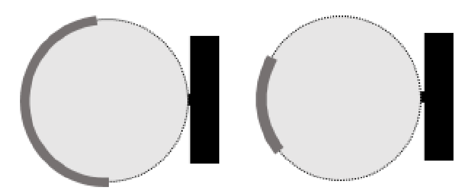

Figure 9: Coverage on a sphere at the near location (left) and at a farther location (right).

When the center of the sphere is determined using a constrained radius fit (as would be done to find the center to center distance for IUT evaluation), that center will be shifted towards or away from the IUT due to the squishing/flaring of the measured points, resulting in an apparent ranging error.

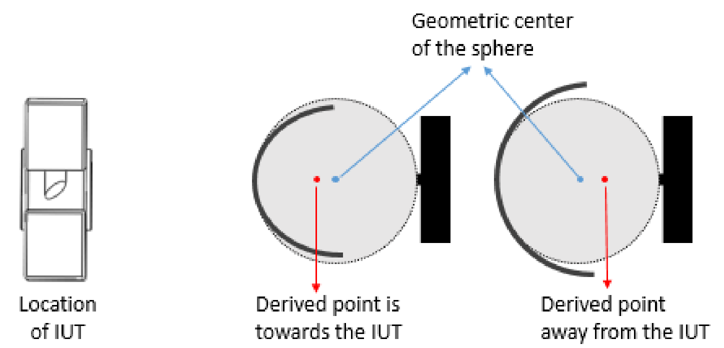

Figure 10: "Squishing" effect (left) and "Flaring" effect (right).

In most cases, the sphere appears to be "squished", rather than "flared". Also, in practice, this affect appears to be more prominent when using phase-based laser scanners than pulse-based laser scanners.

4.2.5 Contrast targets

Contrast targets are popular among the surveying community (depicted in Figure 11). One type of contrast target has planar targets mounted on truncated 1.5 in. (38.1 mm) diameter spheres in such a manner that the center of the truncated sphere lies on the front surface of the target. This center is designed to nearly coincide with the intersection point of the pattern shown in Figure 11.

The truncated sphere allows the contrast target to be mounted on magnetically preloaded kinematic nests. To determine the relative range error, the distance between kinematic nests (at two positions) is first measured using a laser tracker using a 1.5 in. SMR. The SMR is removed and a contrast target is placed in the same nests (one at a time) and scanned using a 3D imaging system [4]. Proprietary algorithms (that use both image intensity and dimensional data) are then used to obtain the derived points of each of the targets and thereby the distance between the two positions using the 3D imaging system.

Since the calculation of the derived point for a contrast target uses a combination of image intensity data and dimensional data, its accuracy and precision is dependent on a variety of factors such as contrast difference, orientation of the target etc. These issues make contrast targets less preferable for use in relative range tests for evaluating the dimensional measurement performance of 3D imaging systems.

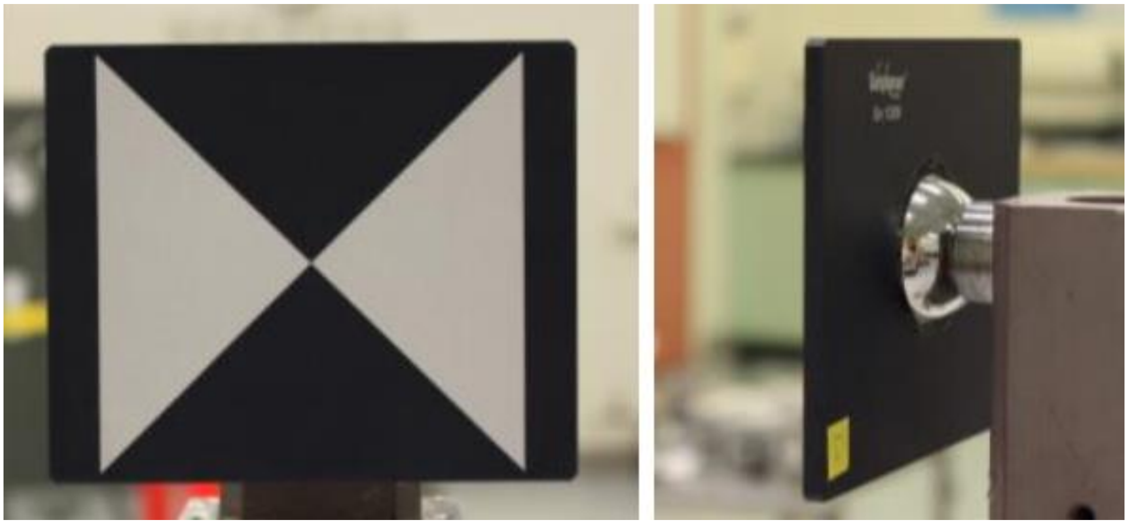

Figure 11: Contrast target front side (on the left) and back side with the truncated sphere mount (on the right)

4.2.6 Pyramid or Polyhedral targets

Pyramid or polyhedral targets attempt to address the shortcomings of the planar and spherical targets. These targets have three or more planes. The derived point of such targets is the apex, which is the intersection of the planes of the target. In case of a trihedral target (triangular pyramid), the intersection of the three planes is unique and is the derived point. In case of a target with more than three planes (e.g. square pyramid), the derived point is the intersection point of the four planes in a least-squares sense.

For a pyramid, the slant angle is the angle that each plane makes with the base of the pyramid (as illustrated in Figure 14). This slant angle is chosen so as to maximize the return signal intensity to the IUT while minimizing the errors associated with determining the intersection point of the planes.

Figure 12: NIST tetrahedral target

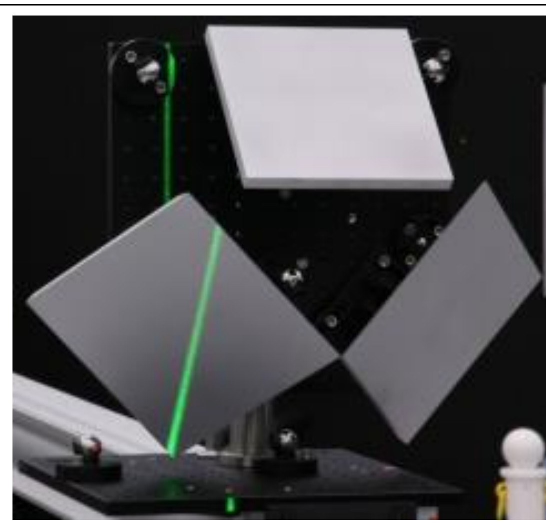

Figure 13: NRC trihedral target [6]

Polyhedral targets constructed with planes at shallow slant angles, say 1°, will not produce a sufficiently repeatable apex coordinate because of the noise in the data from the IUT. Small changes in the location and direction of the normal vector to the best fit planes (to the noisy data) create relatively large changes in the location of the apex. Polyhedral targets constructed with planes at a steep slant angle, say 75°, will also not produce a sufficiently repeatable apex coordinate. This is because of the fewer number of data points acquired on the plane and the fact that these points have higher noise levels due to the steep incidence angle of the laser beam with the plane.

Simulations were performed to understand the effect of the slant angle of a pyramid target on the repeatability of its apex. These simulations indicated that pyramid targets with a slant angles between 10° and 30° yield a sufficiently repeatable derived point (apex) when measured with laser scanner systems.

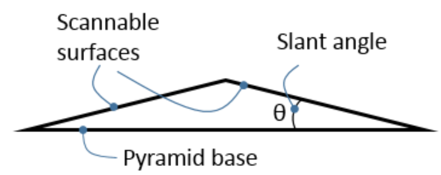

Figure 14: Slant angle of a pyramid artifact.

Determining the derived point using a laser tracker depends on the design of the target. If the target is designed as shown in Figure 12, where the SMR center is designed to be coincident with the apex, a single point measurement is sufficient to determine the target's derived point. For the design depicted in Figure 13, the SMR walking method may be used to manually probe each plane to determine the apex [6,7]. Another method to get the derived point for the same design in Figure 13 is to use three 1.5 in. (38.1 mm) diameter spheres mounted rigidly in kinematic nests on the plate holding the target. The apex of these planes is determined with respect to a coordinate system established by the centers of the three spheres and is calibrated on a CMM. During the relative ranging test, the RI is used along with a 1.5 in. SMR to calculate the apex (using the CMM data) with respect to the locations of the SMR centers located in these three kinematic nests.

The derived point from IUT data is calculated by extracting the data corresponding to each plane of the target, fitting a plane to each data set and intersecting them. The data set for each plane is obtained by excluding the edge points, either manually or by using an automated method.

The pyramid targets have some shortcomings when compared with other targets. The process of extracting a derived point from a pyramid target requires more steps than for other targets. Also, for the target depicted in Figure 12, the SMR needs to be concealed during a scan to avoid any specular reflections from the target.

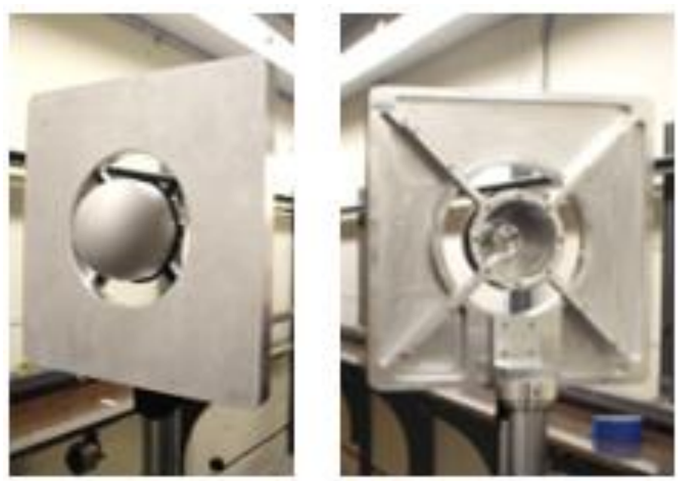

Figure 15: NIST Plate-sphere target

4.2.7 Hybrid targets

Hybrid targets, such as the Plate-sphere target designed at NIST (depicted in Figure 15), leverage the benefits of the geometries of both the sphere and a plane. A plane suffers from the lack of a unique derived point, but can be measured at large distances. A sphere suffers from the fact that its geometry introduces a high variability in determining the radial distance from the scanner to its center. A hybrid target like the NIST Plate-sphere target combines both these geometries to overcome and complement individual target inadequacies

The NIST Plate-sphere target uses a plate target and a 200 mm diameter integration sphere that has a 1.5 in. SMR mounted in its kinematic nest. The derived point for this target is obtained by using a laser tracker and the SMR located inside the integration sphere.

For this target, the 3D imaging system (IUT) and the laser tracker (RI) are placed on opposite sides of the target (as illustrated in Figure 2). The laser tracker measures the sphere center from one side and the laser scanner measures the derived point from the other.

The derived point using the laser scanner is determined using the following series of steps:

1. The sphere and the plane data are individually extracted from the scan data.
2. A least-squares plane is fit to the data corresponding to the plane.
3. A sphere is fit to the data corresponding to the sphere using a non-linear least squares algorithm that constrains the radius of the sphere to its calibrated value (known a proiri).
4. The sphere center is then projected on to the least-squares plane in a direction that is normal to the fitted plane.
5. This projected point is the derived point of this plate-sphere target.

This procedure to obtain the derived point overcomes the issue of high variability of a sphere center in the ranging direction and high variability of the centroid of a plane in the non-ranging directions. It also reduces the need to accurately align the target perpendicular to the laser beam.

One of the drawbacks of the Plate-sphere target is that the sphere occupies a sizeable portion of the center of the plate. When the target is close to the IUT, the data from the plane involves exercising the angular axes and also is not along the line joining the IUT and the RI. Another drawback is that this target is relatively expensive to fabricate.

4.2.8 Alternative designs

To overcome some of the shortcomings of the targets, two more designs are under consideration and are described below:

1. A Plate-sphere artifact with three or more spheres on the outer periphery of the plate to act as a fiduciary instead of a sphere at the center.
2. A Pyramid artifact similar to the one depicted in Figure 12, but designed in such a way that the SMR is accessible from the back of the pyramid.

5 SUMMARY

A variety of targets for use in relative ranging tests were designed and/or procured by DMG at NIST and evaluated. Each target was evaluated objectively based on a variety of desired characteristics, their relative merits and practicality. Each target offers distinctive advantages as well as a few disadvantages for this activity. More work is planned at NIST to improve on the existing designs to evaluate targets for relative ranging.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] ASTM E57.02 – "Test Methods", WK 43218: New Test Methods for Evaluating the Performance of Medium-range, Spherical Coordinate 3-D Imaging Systems for Point-to-Point Distance Measurements.

[2] Muralikrishnan, B., Rachakonda, P., Shilling, M., Lee, V., Blackburn, C., Sawyer, D., Cheok, G., Cournoyer, L., Report on the May 2016 ASTM E57.02 instrument runoff at NIST, Part 2 NIST realization of test procedures and measurement uncertainties, to be published as a NIST internal report.

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

[4] Ferrucci, M., Muralikrishnan, B., Sawyer, D., Phillips, S., Petrov, P., Yakovlev, Y., Astrelin, A., Milligan, S., Palmateer, J., "Evaluation of a laser scanner for large volume coordinate metrology: A comparison of results before and after factory calibration", Measurement Science And Technology, September 2014.

[5] 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.

[6] MacKinnon, D., Cournoyer, L., Beraldin, J., "Single-plane versus three-plane methods for relative range error evaluation of medium-range 3D imaging systems", Proc. SPIE 9528, Videometrics, Range Imaging, and Applications XIII, 95280R (June 21, 2015)

[7] Rachakonda, P., Muralikrishnan, B., Shakarji, C., Lee, V., Sawyer, D., "Evaluation of the Range Performance of Laser Scanners using Non-Planar Targets", Proceedings of the American Society for Precision Engineering, Annual Conference, Austin, Texas, November 01-06, 2015.