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Relative range error evaluation of terrestrial laser scanners using a plate, a sphere, and a novel dual-sphere-plate target

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A B S T R A C T

Terrestrial laser scanners (TLS) are a class of 3D imaging systems that produce a 3D point cloud by measuring the range and two angles to a point. The fundamental measurement of a TLS is range. Relative range error is one component of the overall range error of TLS and its estimation is therefore an important aspect in establishing metrological traceability of measurements performed using these systems. Target geometry is an important aspect to consider when realizing the relative range tests. The recently published ASTM E2938-15 mandates the use of a plate target for the relative range tests. While a plate target may reasonably be expected to produce distortion free data even at far distances, the target itself needs careful alignment at each of the relative range test positions. In this paper, we discuss relative range experiments performed using a plate target and then address the advantages and limitations of using a sphere target. We then present a novel dual-sphere-plate target that draws from the advantages of the sphere and the plate without the associated limitations. The spheres in the dual-sphere-plate target are used simply as fiducials to identify a point on the surface of the plate that is common to both the scanner and the reference instrument, thus overcoming the need to carefully align the target.

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1. Introduction

Terrestrial laser scanners (TLS) produce a 3D point cloud by measuring the range and two angles (azimuth and elevation) to points on the surfaces of objects in a scene. Establishing metrological traceability of TLS measurements is a challenge [1]. The ASME B89.7.5 [2] provides guidance to demonstrate metrological traceability for industrial dimensional measurements. A key step in the ASME B89.7.5 is the development of an uncertainty budget that describes and quantifies the significant uncertainty contributors. In the case of TLS measurements, the error sources may broadly be classified into instrumental errors, errors related to the form and nature of the object, errors caused by the environment in which the scanning is performed, and methodological errors [3]. It is a considerable challenge to quantify these error sources and develop detailed uncertainty budgets for TLS measurements.

As a first step towards quantifying instrument errors, the ASTM E57 committee on 3D imaging systems developed a standard – the ASTM E2938-15 [4] – for relative-range error evaluation of 3D imaging systems. TLS systems generally use time-of-flight (TOF) techniques such as pulsed TOF, phase-based TOF, and frequency-modulated continuous wave (FMCW) techniques for range detection. The ranging unit realizes the SI unit of length and is therefore a key component of the system. Characterizing ranging errors is therefore an important aspect in establishing metrological traceability of TLS measurements. Relative range error is one component of the overall ranging error and can be characterized through a relative range error test. The test involves comparing the distance between two target positions along the ranging direction as measured by the TLS against the same distance determined by a reference instrument that offers higher accuracy such as a laser tracker (LT).

The relative range test may be realized in many ways. We have realized it as shown in Fig. 1 with the TLS located at one end of a long tunnel and the LT at the other end of the tunnel. The target is in-line with the TLS and the LT and has accommodations to move nominally in-line with both instruments. The target is first placed at the reference position (close to the TLS) and both the TLS and the LT measure the target position. The target is then moved to the test position, which is farther away from the TLS than the reference position, and both instruments again measure the target position.

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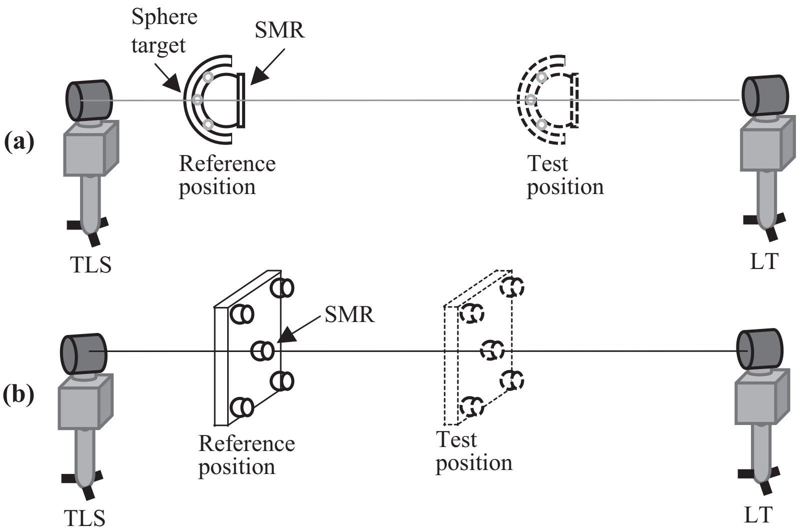

Fig. 1. Schematic of a relative range test using (a) a sphere target and (b) a plate target shown. The reference and test positions are nominally along the line joining the TLS and the LT. Both instruments measure the target at the reference position. The target is then moved to the test position where both instruments measure the target. The relative range error is the difference between the displacement determined by the TLS and that determined by the LT.

The relative range error is the difference in the displacement determined by the TLS and the LT between the reference and the test positions. The target is generally moved to different test positions so that the relative range error (with respect to the reference position) may be determined for different displacements.

The choice of target geometry [5–7] is an important factor in the realization of these tests. The recently published ASTM E2938-15 [4] describes a relative range test for 3D imaging systems using planar targets. The clear advantage of planar targets is that the laser beam strikes the target at incidence angle of nominally zero degrees, hence 3D imaging systems can produce 3D point clouds of these targets even at far distances. However, identifying the point on the plane measured by the TLS that coincides with the point measured by the LT is a challenge. If there is an offset between the two points, small misalignment angles in the orientation of the plate can result in Abbe errors that reflect as a range error.

A sphere target offers the advantage of allowing the determination of a unique derived point, its geometric center. If both the LT and TLS can determine the true geometric center of the sphere, alignment of the target along the line joining the LT and the TLS is not an issue. Some TLS systems, however, may have difficulty in obtaining enough data from the surface of spheres at far distances to reliably determine the sphere center. It is therefore possible that the center determined from such data may result in larger errors in determining the geometric center, which would result in the incorrect determination of the relative range error. Also, large spheres with small form error that are suitable at far distances (50 m or greater) can be expensive.

In this paper, we explore the advantages and limitations of the plate and the sphere target, and propose a novel dual-sphere-plate target that overcomes the limitations of the plate and the sphere target. The spheres in the dual-sphere-plate target are only used as fiducials to identify a point on the surface of the plate (i.e., finding the center of the plate from the TLS data), thus minimizing the errors induced by target misalignments.

2. Reference measurement uncertainty

Reference measurements for the relative range experiment are performed using a LT in absolute distance meter (ADM) mode. For this particular LT, the manufacturer-specified maximum permissible error (MPE) in range is 10 μm. This has been verified in our laboratory by comparing the ADM against our reference interferometer. Using the manufacturer-specified MPE as the upper bound for a rectangular distribution, the standard uncertainty in range measurement for any target position is $10/\sqrt{3} = 6$ μm. The uncertainty in displacement is therefore $6\sqrt{2} = 8$ μm. The $k = 2$ expanded uncertainty due to the LT is therefore 16 μm, which is at least a factor of 10 smaller than the observed errors of the TLS under study.

3. TLS settings

All TLS data are acquired at 92 points per degree along both the azimuth and elevation angle direction. Four scans are acquired at each position of the target. The data are then reduced to the derived point (the center of the plate or the sphere) and results from four scans averaged to attenuate the influence of random effects.

4. Relative range measurements using a plate target

4.1. Plate target

The plate target is fabricated out of aluminum and is shown in Fig. 2. It is 304.8 mm × 304.8 mm (12 in × 12 in) on the front and has a thickness of 25.4 mm (1 in). The front surface is sandblasted to produce a scanner friendly dull gray matte finish. Five 38.1 mm (1.5 in) spherically mounted retroreflector (SMR) nests are glued onto the backside of the plate. One of the five SMR nests is located centrally on the plate and is used for reference measurements with the tracker. The other four SMRs are located on each of the four corners (≈250 mm apart) and are used to align the plate.

4.2. Plate alignment and measurement procedure

When performing relative range measurements, it is important that the center of the plate as determined by the TLS coincides with that determined by the LT to avoid Abbe errors. That is, however, often not possible. In our design of the plate, the center of the SMR (O_1 at the reference position and O_2 at the test position) is