New approach for low-cost TLS target measurement

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Abstract

The registration and calibration of data captured with terrestrial laser scanner instruments can be effectively achieved using signalized targets comprising components of both high and low reflectivity, so-called contrast targets. For projects requiring tens or even hundreds of such targets, the cost of manufacturer-constructed targets can be prohibitive. Moreover, the details of proprietary target center co-ordinate measurement algorithms are often not available to users. This paper reports on the design of a low-cost contrast target using readily-available materials and an accompanying center measurement algorithm. Their compatibility with real terrestrial laser scanner data was extensively tested on six different instruments: two Faro Focus 3D scanners; a Leica HDS6100; a Leica P40; a Riegl VZ-400; and a Zoller+Fröhlich Imager 5010. Repeatability was examined as a function of range, incidence angle, sampling resolution, target intensity and target contrast. Performance in system self-calibration and from independent accuracy assessment is also reported. The results demonstrate compatibility for all five scanners. However, all datasets except the Faro Focus 3D require exclusion of observations made at high incidence angles in order to prevent range biases. Results also demonstrate that the spectral reflectivity of the target components is critical to ensure high contrast between target components and, therefore, high-quality target center co-ordinate measurements.

Key-words

Terrestrial laser scanning, contrast target, target measurement, registration, self-calibration

Introduction

Structured targets are essential equipment for terrestrial laser scanner (TLS) data capture. They are routinely used to facilitate the transformation of multiple scans of large, complex environments (Hullo et al., 2015) into a common co-ordinate system. A minimum of three—but preferably more—non-collinear targets should appear in each scan. The rigid body transformation parameters for each scan can be estimated in closed form (Horn, 1987) from the observed (in scanner space) and independently-surveyed co-ordinates of the target centers. Structured targets are also used for calibration to estimate instrumental systematic errors.

Large arrays of up to 200 structured targets have been demonstrated to be versatile for TLS system self-calibration (Lichti, 2007; Reshetyuk, 2010).

TLS systems usually include a set of fabricated targets that may be monotone spheres or planar discs with a checkerboard pattern, so-called contrast targets (Fig. 1). Spheres are generally advantageous in that they are omnidirectional. Although a set of 10-12 spherical or planar targets may be sufficient for scan registration on many projects, many more may be required for very large projects and self-calibration. The purchase of 100 to 200 pre-fabricated targets can be prohibitively expensive, so a low-cost alternative is needed. Paper contrast targets are inexpensive and many can be printed from manufacturer-provided templates onto A4 or Letter size sheets. However, paper targets are not rigid and are strongly affected by humidity changes over time, leading to target deformation. Thus, they are essentially temporary, disposable targets not well suited for a permanent calibration facility setup.

As noted by Ge and Wunderlich (2015), the details of target center measurement methods are not provided by the instrument manufacturers. Accordingly, several researchers have reported contrast target measurement algorithms. Lichti et al. (2007) report using circular black-and-white paper targets for TLS self-calibration, specifically the Surphaser 25HS. Its basis is a plane fit of the 3D target measurements using orthogonal regression followed by a 2D circle fit to edges detected in a resampled image. The method reported by Chow et al (2010) builds on this algorithm for testing of the Trimble GX scanner.

Ge and Wunderlich (2015) report a method for 2x2 circular checkerboard target measurement. They also first perform a plane fit for the target data, favouring the 2.5D parameterization $z=f(x,y)$. Next, the return signal intensity values are classified by robustly estimating an intensity threshold. Line fitting and subsequent line intersection are performed to estimate the target center co-ordinates. They report the performance of their method at different resolutions and distances for one scanner, the Leica HDS7000, over on a calibration track. Laser tracker data serve as the reference for accuracy assessment. All analyses are conducted in Cartesian co-ordinates. An algorithm for 2x2 circular checkerboard target center estimation is also described in Liang et al. (2014) but results for only three targets are presented.

Rachakonda et al. (2017) report two methods for the measurement of 2x2 square checkerboard contrast targets in support of TLS instrument calibration described in detail by Muralikrishnan et al. (2015). The target area is first manually cropped from the point cloud. This is followed by circular mask cropping of the target and generation of a 2D image of the target area. Lines defining the boundaries between the target components are identified by Canny edge detection, extracted with the Hough transform and then intersected. Their 2D images comprise both intensity and spatial co-ordinates as dependent variables, so interpolation is used to determine the center co-ordinates in their first method. In their second method, the scanner data are first artificially densified by cubic interpolation. Their methods are compared with three commercial software packages in terms of repeatability with 25 targets. The maximum incidence angle tested was 50°.

The aim of this work was to develop and test a new, low-cost target design and measurement algorithm. The targets comprise a Compact Disc (CD) mounted on a dark background. CDs were chosen due to their ready availability, rigidity and low cost. Based on the method reported by Lichti et al. (2007), it features several key improvements including the use of known CD dimensions for target segmentation, a rigorous method for deriving the 2D image resolution that preserves information content and an iterative target segmentation process to exclude unwanted background points from the plane fit. Moreover, extensive testing has been performed to thoroughly examine algorithm performance. Six different TLS instruments were tested over a dense target field. Repeatability was assessed in detail with multiple datasets captured from different locations. Performance was examined as a function of several variables: range (up to 10.5 m), incidence angle (up to 80°), sampling resolution, target intensity and target contrast. Performance in system self-calibration and an independent accuracy assessment are also reported. As a result of the testing regime, recommendations are made about the suitability of the proposed target design and measurement algorithm for each scanner.

Target Measurement Algorithm Description

Pictured in Fig. 2, the custom-built TLS target features a Compact Disc painted matte white and bonded to a rigid, matte black cardstock board (200 mm x 200 mm x 2 mm). This design provides high contrast between the foreground and background components. CDs are manufactured with a spindle diameter of 15 mm and an outside diameter of 120 mm. These known dimensions are used in several steps of the measurement algorithm.

The first step is extraction of the target area from an acquired point cloud. In this work, a circular region around each target was manually extracted (Fig. 3), though there is high potential to automate this process to a great degree for a calibration target field with known co-ordinates. Each individual target area is identified automatically from a text file of the point cloud of all cropped targets. The target co-ordinates are translated to their centroid then fit to a plane using the eigenvalue decomposition of their 3x3 covariance matrix (Shakarji, 1998). Note that at this stage, both foreground CD and background samples are included in the plane fit. The data are transformed from the scanner-centric xyz system to the target-centric uvw system defined by the eigenvectors: the u and v axes lie in the best fit plane and w is orthogonal to it (Fig. 4).

The next step is to create a uniformly-sampled intensity image of the target area from the irregularly-spaced samples in the uvw system. The selection of the sampling interval for the image is critical so as to preserve information content. To this end, the convex hull of the target point cloud is constructed. The mean point spacing is computed as the square root of the convex hull area normalized by the number of point cloud samples. This assumes that point spacing within the target plane is homogeneous and isotropic. The irregularly-spaced 2D points are resampled using bilinear interpolation to produce an intensity image having sampling intervals in u and v both equal to the mean point spacing.

Canny edge detection produces a binary image of edge points. To exclude unwanted edge points, only those lying between the inner spindle and the outside radii are retained. A closed-form, least-squares 2D circle fit of identified points on the circumference of the CD (Förstner and Wrobel, 2004) is then performed (Fig. 5). Note that the known outer radius of the CD is not used as a constraint in the circle fit; the estimated radius is instead compared with the known value as a quality control measure. Experiments were performed to determine the Canny edge detector high and low thresholds and the standard deviation. In the end, the default MATLAB values of 0.3, 0.6 and 1.41, respectively, were chosen to be used for all datasets. Changing the parameters could influence edge location around the circumference, and hence estimated radius. However, the center location of the circle fit was not influenced due to the high-contrast, symmetric target design within the parameters (range and incidence angle) of the experiment.

The estimated circle center (u_c, v_c, 0) is transformed back into the xyz scanner-centric system to obtain the target center co-ordinates in, (x_c, y_c, z_c). A known source of systematic error in the measurement of the center position of circular (Ahn et al, 1999) and spherical (Luhmann, 2014) targets in central perspective images is target eccentricity. However, since the circle fitting is performed in the target plane in object space rather than in a projected intensity image plane, the resulting measurements are free from any target eccentricity error.

Since the plane fit was performed using both foreground and background points, which lie in different planes due to the CD thickness, the center estimate is biased. Thus, a second iteration of the entire process is performed to produce a more accurate target center. The estimated target center and known CD radii are used to exclude all central and background points from the plane fit operation; only points on the CD surface itself are included. Finally, the incidence angle is estimated from the center position vector and best-fit plane normal from the second iteration.

Experiment description

Experiments to test the new target design and center measurement algorithm were conducted in a 10 m x 9 m x 4.3 m calibration room (Fig. 6). Two hundred (200) custom-built CD targets were mounted with high-bond adhesive tape on the walls, the floor and the ceiling of the room.

Data were collected with several different instruments from different manufacturers: two Faro Focus 3D scanners; a Leica HDS6100; a Leica P40; a Riegl VZ-400; and a Zoller+Fröhlich (Z+F) Imager 5010. Two datasets were recorded with each Faro instrument and the HDS6100 scanner. Room temperature ranged between 20 and 22°C for the experiments that took place over the course of one month. The data capture settings varied depending on instrument, but the following general principles were obeyed: level compensation was used where available and high resolution and high quality data were collected.

Scans were captured from three nominal locations within the room: two in corners, at least 1.2 m from each wall; and one in the center. The scanner height above the floor was 1.25 m. At each location the instrument tripod was affixed to a spider mount which in turn was affixed to the floor so as to prevent movement of the assembly during data collection. Three scans were captured at each location. The instrument was rotated by 120° for each successive scan by removing it from the tribrach and manually rotating it. An extra scan was captured at one of the instrument locations for one of the Focus 3D datasets.

The high redundancy and strong geometric design of the scanning network permitted the use of a number of quality assessment methods. Repeatability could be assessed since multiple point clouds were captured with each instrument from different locations and with different orientations. Algorithm performance was assessed in terms of plane fit precision, circle fit precision and estimated radius as a function of several variables:

- Range, ρ: from 1 m to 10.5 m;
- Incidence angle, β: 0° to 80°;
- Target sampling resolution, Δ_x: 1 mm to 13 mm; and
- Target intensity, E.

The precision of plane and circle fits was measured by the root mean square error (RMS) of the residuals.

A least-squares, free network self-calibration adjustment was also performed for each dataset following the procedure described in (Lichti 2007). The objective was to determine whether the target measurement algorithm introduced any systematic error source in addition to instrumental biases that may exist. Self-calibration is an effective tool for this purpose. Given a highly redundant dataset, a minimally-constrained datum, strong first order network design and a properly constructed stochastic model, the estimated residuals from such an adjustment can reveal whether the data are corrupted by un-modelled systematic errors. Additional parameters (APs) that describe known instrumental systematic errors were estimated in the adjustment. The choice of which APs from the set proposed by (Lichti 2007) to include for a particular instrument was made with the aid of graphical and statistical analyses in order to model all systematic effects but avoid over-parameterization. Starting from the case with no APs, the model was built stepwise, adding a single AP and re-running the adjustment at each trial until all instrumental effects were compensated. Once the instrumental error modelling was complete, the residuals from the final adjustment were analyzed for systematic trends that may be introduced by the target algorithm.

Target reconstruction accuracy was assessed by comparing the TLS-determined target co-ordinates with independently-surveyed co-ordinates. Sixty-one (61) of the targets were surveyed with a Leica TS30 total station from four different locations in the room. Direction and zenith angles were observed with the cross-hairs tangent to the CD targets on two faces. Scale was defined by a 0.9 m Leica scale bar (σ = 0.02 mm). The co-ordinate precision from free network adjustment was 1.1 mm in both X and Y and 0.3 mm in height at the 95% confidence level. Co-ordinates from two TLS cases were compared for each dataset, no APs and final AP set, in order to quantify accuracy improvement. A rigid body transformation was estimated for each dataset to ensure that the surveyed and TLS co-ordinates were in the same system for direct comparison

Experiment results

Many results were generated in this investigation. In order to provide a concise description of the outcomes, only representative results as well as anomalous findings are presented for all cases.

Target contrast

The two sides of the black board used for the target background are slightly different. Though difficult to discern with the naked eye or by touch, one is slightly rough and the other is slightly smooth. The differences in their reflectance spectra measured by spectroradiometer (ASD FieldSpec Pro FR; Fig. 7) are very pronounced. The spectrum of the slightly rough side is effectively constant over the 500 nm to 2500 nm range, whereas the slightly smooth side is non-uniform. Some targets were constructed with the rough side facing outward, while others were built with the smooth side facing out. In general, the smooth-background targets exhibited poor contrast for all instruments. Examples are shown for the P40 and the VZ-400 (Fig.s 8 and 9, respectively). Many outliers existed in the data as a result. The outliers can be identified relatively easily with the contrast ratio, C, defined as

$$C = \frac{\bar{E}_{fg} - \bar{E}_{bg}}{\bar{E}_{fg} + \bar{E}_{bg}} \tag{1}$$

where $\bar{E}_{fg}$ is the mean foreground (white CD) intensity and $\bar{E}_{bg}$ is the mean background (black cardstock) intensity. Systems that provide negative intensity measures can be accommodated with linear transformation of the intensity values.

As can be seen from the examples in Fig. 10, the lower-quality, smooth-background targets are easily identified from the plot of plane fit residual RMS as a function of contrast. A simple thresholding operation is sufficient to remove the low-contrast targets. For all subsequent analyses, only the rough-background observations are analyzed.

Performance as a function of range

Performance as a function of range is first assessed by analyzing the RMS of range residuals from the plane fitting. Examples from the second Focus 3D scanner and the Leica P40 dataset are shown in Fig. 11. Two observations can be made from the Focus 3D and P40 results. First, there are many outliers in the data, identified by the rectangles. The cause of these outliers will be discussed shortly. Second, the overall trend of the plane fit precision is slight degradation with range, which is expected. The results from the other scanners follow similar patterns.

The quality of the circle fit, as measured by the RMS of co-ordinate observation residuals (Fig. 12), and the estimated target radius (Fig. 13) were also analyzed. The HDS6100 results show two trends. The linear trend between 2 m and 8 m represents biases caused by observation at high incidence angle, which is analyzed in the next section. The constant trend component shows that, apart from the biases, circle fit precision is independent of range. The Imager 5010 results show similar behaviour. No range dependence is evident in the Focus 3D results, which is also true for the other scanners' datasets.

Performance as a function of incidence angle

For all datasets, the plane fit residuals in the range direction follow the theoretical behaviour as a function of the secant of the incidence angle, β (Soudarissanane et al., 2011). The many outliers observed as a function of range in Fig. 11 for the Focus 3D and HDS6100 occur at high incidence angles (Fig. 14).

The circle fit (Fig. 15) and radius estimates (Fig. 16) present perhaps the most interesting results thus far. The Focus 3D and VZ-400 scanners exhibit a slight improvement in circle fit precision, while the P40 precision is independent of β. In contrast, the circle precision for the Imager 5010 (and the HDS6100, not shown) degrades at high incidence angles. All radii estimates are constant and slightly biased relative to the expected 60 mm CD radius as a result of the chosen edge detector parameters, though only by up to about one half of a millimeter. The Focus 3D and VZ-400 radii are systematically larger and the former increases at high incidence angles. The other three scanners' radii are systematically smaller with the Imager 5010 (and HDS6100) radii becoming unreliable above about 60°. The cause of this effect is described in the self-calibration results section.

Performance as a function of resolution

For all datasets, plane fit precision exhibits a linear trend as a function of sampling resolution, which is expected, in addition to the aforementioned outliers. Two examples are shows in Fig. 17: a Focus 3D, which features a large range of sampling resolutions (approximately 1 mm to 10 mm) and the Leica P40 for which the range is lower (1 mm to 4 mm). No dependence exists in circle fit quality in these or other datasets except for the HDS6100, which shows incidence angle effects.

Self-calibration results

The final degrees-of-freedom (dof), the number of APs and the before- and after self-calibration residual statistics are reported in Table 1. The dof are higher for one of the Focus 3D datasets due to the tenth scan. The dof are lower for the HDS6100 and Imager 5010 due to exclusion of observations above the reported incidence angle (β) threshold, which is explained shortly. For the P40 and VZ-400, the dof are much lower due to two factors: exclusion of observations above the reported incidence angle threshold and exclusion of the aforementioned poor quality targets.

All APs estimated model physical effects; no empirical model terms were necessary. The estimated APs for range included the rangefinder offset and periodic range error terms. For horizontal direction, the estimated APs included the collimation axis error, the trunnion axis error and non-orthogonality of the horizontal angle encoder and the vertical axis. Finally, the elevation angle errors included the vertical circle index error and the vertical circle eccentricity error.

In some cases, the Faro instruments in particular, the addition of the APs yielded considerable improvement to the RMS of the angular residuals. In other cases, the addition of the APs yields only small (sub-millimeter or a few arc seconds) improvement to the RMS of the residuals. However, all model trends that were visible in graphical representations of the residuals and are statistically significant at the 95% confidence level.

All datasets except those from the Focus 3D exhibited a range bias as a function of incidence angle (Fig. 20). This is particularly interesting given that the Faro datasets featured systematic increases in target radius with incidence angle. The bias is non-existent when the incidence angle (β) is low but is readily apparent for angles greater than 60° or 65°, depending on the instrument.

Graphical analysis of the targets gives insight into the cause of the range bias. Fig. 21 shows the intensity image for two targets observed at high ($\beta > 75°$) incidence angles. Each one exhibits a bright fringe on part of the CD circumference on the side closest to the scanner. This high intensity leads to detected edges pixels that are displaced toward the scanner and, in turn, biased center co-ordinates. The derived range to the target is therefore systematically short, hence the positive residuals from the self-calibration adjustments. The reason for this behaviour is not known, but could be due to multipath reflection from the edge of the CD if not completely painted. Further investigation is required to ascertain the exact cause. In the meantime, the practical solution to overcome the problem is to exclude observations above a suitably-chosen threshold, which was followed for the self-calibration adjustments except for the Faro datasets.

Accuracy assessment

The RMS of co-ordinate differences are reported in Table 2. All datasets exhibit accuracy improvement as a result of including the APs, with the exception of the Imager 5010. All accuracy measures are sub-millimeter and are within the precision of the targets, except for Faro #2 for which accuracy is slightly lower. Thus, it can be concluded that there is no bias introduced by the target design or center measurement algorithm at the millimeter level.

Conclusions

Structured targets are essential for TLS registration and system calibration. A new low-cost target design and center measurement method has been presented and its performance examined as a function of a number of key variables. Several phenomena were observed from the results and conclusions can be drawn about the suitability of the target design and algorithm for each instrument.

The Faro Focus 3D data can be considered compatible with the CD-based target and measurement algorithm. No range biases were introduced and there was no need to exclude data above an incidence angle threshold. However, an additional test was conducted in which observations with incidence angle greater than 65° were excluded. No significant changes to the self-calibration results were observed. Data from the other scanners can also be considered compatible. However, observations above a critical incidence angle should be excluded in order to prevent range biases to the target center caused by the CD edge illumination phenomenon shown in Fig. 21. In addition, the spectral reflectivity of the target materials should be observed to prevent collection of data with poor contrast.

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Table 1. Self-calibration adjustment results for all datasets.

Scanner	dof (with APs)	# significant APs	β cut-off (°)	RMS of residuals—no APs			RMS of residuals—with APs		
				ρ (mm)	θ (″)	α (″)	ρ (mm)	θ (″)	α (″)
Focus 3D #1 Dataset 1	4403	7	N/A	1.5	53	33	1.1	24	21
Focus 3D #1 Dataset 2	4967	7	N/A	1.3	47	34	0.9	22	20
Focus 3D #2 Dataset 1	4423	5	N/A	1.1	31	32	1.0	25	24
Focus 3D #2 Dataset 2	4381	5	N/A	1.0	36	42	1.0	25	25
HDS6100 Dataset 1	3590	4	60	0.5	19	20	0.4	17	17
HDS6100 Dataset 2	3566	4	60	0.5	19	19	0.5	17	16
P40	2102	1	65	0.5	19	19	0.5	18	19
VZ-400	1959	3	65	1.0	24	23	0.9	23	23
Imager 5010	3276	0	65	0.6	24	19	-	-	-

Table 2. Accuracy assessment results for all datasets.

Scanner	RMS of co-ordinate differences—no APs			RMS of co-ordinate differences —with APs		
	X (mm)	*Y* (mm)	*Z* (mm)	*X* (mm)	*Y* (mm)	*Z* (mm)
Focus 3D #1 Dataset 1	1.4	1.5	0.5	0.9	0.9	0.3
Focus 3D #1 Dataset 2	1.2	1.4	0.5	0.6	0.7	0.4
Focus 3D #2 Dataset 1	1.6	1.5	0.5	1.2	1.1	0.4
Focus 3D #2 Dataset 2	1.7	1.7	0.7	1.4	1.4	0.4
HDS6100 Dataset 1	0.8	0.7	0.6	0.5	0.5	0.4
HDS6100 Dataset 2	0.9	0.9	0.4	0.8	0.7	0.3
P40	1.2	1.0	0.7	0.8	0.7	0.6
VZ-400	1.1	0.9	0.4	0.8	1.0	0.6
Imager 5010	0.9	0.8	0.5	-	-	-