Article

Decreasing the Uncertainty of the Target Center Estimation at Terrestrial Laser Scanning by Choosing the Best Algorithm and by Improving the Target Design

Jannik Janßen *, Tomislav Medic, Heiner Kuhlmann and Christoph Holst

Institute of Geodesy and Geoinformation, University of Bonn, 53115 Bonn, Germany;
t.medic@igg.uni-bonn.de (T.M.); heiner.kuhlmann@uni-bonn.de (H.K.); c.holst@igg.uni-bonn.de (C.H.)

* Correspondence: j.janssen@igg.uni-bonn.de

Received: 7 March 2019; Accepted: 6 April 2019; Published: 8 April 2019

Abstract: During the registration and georeferencing of terrestrial laser scans, it is common to use targets to mark discrete points. To improve the accuracy of the registration, the uncertainties of the target center estimation (TCE) have to be minimized. The present study examines different factors influencing the precision of the TCE. Here, the focus is on the algorithm and the target design. It is determined that, in general, the uncertainties of the TCE are much smaller than those indicated by the manufacturers. By comparing different algorithms for the first time, it was possible to clearly determine that an algorithm using image correlations yields the smallest standard deviations for the TCE. A comparison of different target designs could not identify an ideal commercially available target. For this reason, a new target, the BOTA8 (BOnn TArget with 8-fold pattern) was developed, which leads to smaller standard deviations than the previous targets. By choosing the best algorithm and improving the target design, standard deviations of 0.5 mm in distance direction and 1.2 arcsec in angular direction for a scan distance up to 100 m were achieved with the laser scanner Leica ScanStation P20. The uncertainties could be reduced by several millimetres and angular seconds compared to the manufacturer's targets and software.

Keywords: terrestrial laser scanning; target center estimation; target design

1. Motivation

In recent years, terrestrial laser scanning (TLS) has become an established measuring technique in engineering geodesy. For many TLS applications, laser scanning targets are employed, as for example in the data acquisition of a measured object from different stations or in deformation monitoring [1,2]. In these cases, target coordinates extracted from the 3D point cloud are used to register the single point clouds to a joint point cloud. Another example of the application of targets is the calibration of laser scanners. Here, the target center coordinates are used to determine systematic errors of the laser scanner's construction [3,4]. Especially for these two examples (registration and calibration), a highly precise target center estimation is required in order to achieve likewise precise results for the registration of point clouds or the calibration of laser scanners.

In many cases, plane black and white targets with checkerboard pattern are applied as shown in Figure 1. Based on the measured three-dimensional coordinates of the target and its intensities, the target center is estimated from the point cloud by means of an algorithm. Although targets are widely used, the uncertainties of the target center estimation (TCE) have hardly been investigated [5] yet. This study discusses the influence of the laser scanner, scan geometry, atmosphere, target design, and algorithm on the uncertainty of the TCE. Although their connections to the uncertainty of the

TCE are explained in more detail in Section 2, it is already mentioned that this paper will focus on the investigation of the algorithm and the target designs.

In order to compare the influencing factors, it is essential to first define a measure for the quality of the TCE. The uncertainty of the TCE generally includes both systematic and random errors [6,7]. All factors influencing the uncertainty of the TCE are discussed below with respect to their random and systematic errors.

Figure 1. Left: image of a plane black and white target with checkerboard pattern (Leica Tilt&Turn-Target), right: scanned point cloud of the target (intensity-colored).

All in all, this paper aims to answer four questions:

1. How accurate is the TCE in general?
2. How large is the influence of the algorithm on the TCE?
3. How large is the influence of the target design on the TCE?
4. How can the accuracy of the TCE be increased?

This paper is structured as follows: Section 2 explains the factors influencing the uncertainty of the TCE in more detail. Section 3 examines the influence of the selected algorithm on the uncertainty and Section 4 examines the influence of different target designs. Section 5 summarizes the findings and offers perspectives for future research.

2. Influencing Factors on the Precision of Target Center Estimation

The influencing factors on the precision of the TCE can be defined analogously to the influencing factors of the single point measurement according to Zogg [8] and Soudarissanane [9], whereby the four influencing variables are extended by the influence of the algorithm estimating the target center (Figure 2):

1. **Laser scanner:** The influence of the laser scanner on the uncertainty of the TCE essentially depends on two variables:
 - (a) The uncertainty of the scan points: Random errors of the angle and distance measurements lead to random errors in the three-dimensional point cloud, which is used for the TCE [10]. The systematic errors of the laser scanner shift the target center systematically. However, eliminating these systematic errors is the task of laser scanner calibration [3,11]. The systematic errors of the laser scanner are therefore not considered in this study.
 - (b) The angular resolution and divergence of the laser beam: They define the effective spatial point density on the target [12,13]. It is assumed that a higher point density can lead to a more precise TCE than a lower point density, since the transition between black and white parts can be reconstructed sharper.

Both points lead to the fact that the precision of the TCE differs for different laser scanners and angular resolution settings.

2. **Scan geometry:** The geometry includes the distance and the incidence angle of the laser scanner to the target [14]. The returning intensity of the laser beam decreases with increasing distance, as well as with increasing incidence angle [15,16]. This leads to a decrease in the precision of the point cloud [17,18]. Since the target center is estimated from this point cloud, it can be assumed

- that the geometry also has an influence on the precision of the TCE. Zámečníková et al. [19] show that systematic errors in the single point measurement can also occur due to the incidence angle.
3. **Atmosphere:** As with all electro-optical distance measurements, the atmosphere has an influence on the precision of the point. Due to the usual target distances of a few hundred meters and the sufficient correction models, which take temperature, air pressure, and humidity into account [20], it is of minor importance for TLS and thus also for the precision of the TCE. Therefore, the atmosphere will not be considered further in the following.
 4. **Target design:** It is known from the literature that the properties of the measured object, such as material, surface finish, color, and reflectivity, also affect the precision of the point cloud [8,10,21]. As with scan geometry, it can be assumed that the precision of the single point also influences the precision of the TCE. In addition to the object properties mentioned, the shape and pattern of the target have to be considered. A detailed description of these properties can be found in Section 4.1. Some studies have already investigated isolated parameters of targets [22–24], but no comparison of different commercially available targets has been made yet.
- When using spherical targets, systematic errors can occur due to one-side scanning of the target [23,25]. These systematic errors are referred to as “squishing” and “flaring” effects. Therefore, only plain black and white targets are considered in the following.
5. **Algorithm:** From the point cloud recorded by the laser scanner, the coordinates of the target are estimated by means of an algorithm. For this, there are multiple algorithmic approaches [26–28]. It is assumed that not all algorithms provide equally precise coordinates. Hence, the following section investigates different algorithms for the TCE.

Figure 2. Influencing factors on the precision of the target center estimation (TCE).

The consideration of the influencing factors with regard to the systematic and random errors in the TCE comes to the following conclusion: systematic deviations can be largely eliminated by calibrating the laser scanners, by corrective models of the atmosphere, and by using flat targets. The algorithms are assumed to be unbiased, thus no systematics are expected. Only the systematic errors due to the incidence angle [19] remain. However, since the incidence angles during the scanning of targets are usually small and the error on the TCE will behave the same as for the single point measurement, this systematic error will not be examined further.

Finally, only random errors remain, which can be caused by the laser scanner, the scan geometry, the target design, and the algorithm. In order to describe the accuracy of the TCE, it is therefore sufficient to quantify just the precision of the TCE using empirical standard deviations $\hat{\sigma}$ from multiple measurements.

The following sections focus on quantifying the influences of the algorithm and of the target design. However, the influence of the scan geometry is considered in the experiments. Furthermore, the experiments were carried out with different laser scanners and different resolutions. The latter experiments are not explicitly shown here, since the findings for the algorithms and target designs are similar.

3. Influence of the Algorithm on the Uncertainty of the Target Center Estimation

The aim of the algorithm for the TCE is to estimate the coordinate of the signalled discrete point of a target from the recorded point cloud. For this purpose, different approaches and algorithms

exist, which are described in Section 3.1. In Section 3.2, the estimates of the different algorithms are empirically compared.

3.1. Algorithmic Approaches for Target Center Estimation

The users of terrestrial laser scanners often apply the respective manufacturer software for the TCE. The methodology of the algorithms applied in this software is usually kept secret for competitive reasons. For details on existing methodological approaches for TCE algorithms, scientific publications can be considered. Here, a number of different algorithms for the TCE can be found, which are described in their basic principles. In Table 1, the previous publications are divided into three categories (A–C) according to their methodological approaches.

Table 1. Literature overview of algorithms for the target center estimation (TCE) categorized into three methodological approaches.

Category	Methodology	Publication
A	Averaging techniques	Lichti et al. [29] Gordon et al. [30] Valanis & Tsakiri [31]
B.1	Edge detection	Eling [32] Chow et al. [33]
B.2		Chow et al. [26] Ge & Wunderlich [27] Rachakonda et al. [34]
C.1	Image correlation	Abmayr et al. [35] Liang et al. [36]
C.2		Yi et al. [37] Omidalizarandi et al. [38] Kregar et al. [28]

Category A: The first TCE algorithms based on simple averaging techniques were published in the early 2000s [29,30]. These were improved in the following years and further developed [31], but their uncertainties remained in the range of several millimeters to centimeters. Therefore, this category of algorithms has no scientific relevance anymore.

Category B: The algorithms of this category use the edges between the black and white areas of the targets for the TCE. For instance, an intensity image is derived from the point cloud and the edges are extracted using image gradients (Cat. B.1) [32,33]. The first publications of this approach referred only to radial symmetric targets, later the method was extended to the widely used checkerboard targets by Chow et al. [26]. In Section 3.1.1, such an algorithm is described in more detail. The algorithms of category B.2 extract the edges of the black and white transitions not from intensity images but directly from the intensities of the measured points [27,34]. An algorithm of category B.2 is described in detail in Section 3.1.3.

Category C: The last category of algorithms is based on the TCE using correlations. Either the symmetry of the targets is used to find the targets in an intensity image (category C.1) [35–37] or the coordinates of the signalised points are estimated with a template (category C.2) [28]. This approach is also used for determining target centers in RGB images obtained by image-assisted total stations [38].

From previous publications, the algorithms of category C.1 seem more suitable for the coarse identification of targets in an intensity image and not for a precise coordinate estimation. Therefore, the algorithms of this category are not considered further. In contrast, the approach of category C.2 allows a precise estimation of the target center [28]. In Section 3.1.2, an algorithm of category C.2 is described in more detail.

Figure 3 shows the flow diagrams of the three algorithms described in the following Sections. The algorithms were supplemented by reasonable assumptions, where undefined or unclear details occurred from the previous literature.

Figure 3. Workflow of the three algorithms described in Sections 3.1.1–3.1.3.

3.1.1. Algorithm Using Image Gradients (B.1)

The algorithm using image gradients (Cat. B.1) described in the following is mainly based on the paper of Chow et al. [26]. The algorithm can be structured into five main steps:

1. **Plane fitting:** Since the algorithm is limited to plane targets, a plane can first be estimated through the point cloud $\mathbf{X}$ of the target. The RANSAC algorithm [39] is used to estimate a plane and thus identify all points that belong to this plane. Then, a final plane is estimated through the identified points of the target plane using the least squares adjustment [40]. To ensure a correct plane estimation, the stochastic model of a single point with its distance standard deviation σ_r and angular standard deviation σ_w has to be considered. After the plane estimation, the points are projected into the plane according to their residuals. So, in the following, the component orthogonal to the plane is neglected and only the remaining 2D point cloud $\mathbf{X}_p$ is considered.
2. **Intensity image:** The 2D point cloud $\mathbf{X}_p$ is segmented into grid cells to derive an intensity image $\mathbf{I}$ from the point cloud. Each grid cell forms a pixel to which a unique x and y coordinate can be assigned. The grey value of the pixel is interpolated from the intensities of the point cloud. The pixel size is theoretically arbitrary, but further investigations in preparation for the present study have shown that a pixel size smaller than 1 mm does not further improve the precision of the algorithm. Therefore, the pixel size is set to 1 mm in this paper.
3. **Edge detection:** The edges between the black and white areas of the image are now extracted from the intensity image $\mathbf{I}$ with the help of image gradients. For this, the Canny algorithm [41] is used. As a result, an edge image $\mathbf{E}$ is obtained.
4. **Line fitting:** The extracted edge pixels are used to estimate two lines, which represent the transitions of the checkerboard pattern. Again, the RANSAC algorithm first estimates the two best lines through all edge pixels in $\mathbf{E}$ to classify whether the pixels belong to one of the two lines and if so, to which line. These pixels are then used to estimate the two best lines $\mathbf{g}_1$ and $\mathbf{g}_2$ using a least squares adjustment.
5. **Final coordinate calculation:** From the intersection of the two lines $\mathbf{g}_1$ and $\mathbf{g}_2$, the two-dimensional coordinates of the target center are obtained. The plane parameters from step 1 are used to transform the coordinate back into the three-dimensional space and to obtain the final 3D coordinate of the target center.

3.1.2. Algorithm Using Image Correlations (C.2)

The algorithm using image correlations with an artificial template (Cat. C.2) is mainly based on the paper of Kregar et al. [28]. The algorithm can be structured into four main steps:

1. **Plane fitting:** Same procedure as for the algorithm using image gradients, see Section 3.1.1.
2. **Intensity image:** Same procedure as for the algorithm using image gradients, see Section 3.1.1.
3. **Image correlation:** An artificial template is generated, which contains an image of an ideal black and white target. Then, the cross-correlations between the template and the intensity image are calculated. For the location, where the image correlation is highest, the x and y values are taken from the grid of step 2 and the 2D coordinate of the target is derived. This procedure can also be referred to as correlation-based image registration.

In order to extend the approach of Kregar et al. [28] from radially symmetric targets, such as circles, to targets with checkerboard pattern, this step is repeated for different rotations of the template. The 2D coordinates of the different rotations with the highest overall image correlation gives the best solution. The step size used for the various rotations is set to 1° because further investigations in preparation for the present study have shown that smaller step sizes have no influence on the precision of the algorithm.

In order to improve the precision of the algorithm, the translations are estimated in the subpixel range, according to the method described by Guizar-Sicairos et al. [42].

4. **Final coordinate calculation:** The location with the highest image correlation already provides the 2D coordinate of the target center. With the help of the plane parameters from step 1, the 2D coordinate can be calculated into the aimed 3D coordinate of the target center.

3.1.3. Algorithm Using Middle Intensities (B.2)

The algorithm using middle intensities (Cat. B.2) described in the following is mainly based on the paper of Ge & Wunderlich [27]. The algorithm can be structured into four main steps:

1. **Plane fitting:** Same procedure as for the algorithm using image gradients, see Section 3.1.1.
2. **Edge detection:** The idea is to extract the edges directly from the intensities of the scan points. Hence, no intensity image is generated in contrast to the algorithm using image gradients. It is assumed that points which lie on the edges between the white and black areas also have middle intensity values. Ge & Wunderlich [27] named them “middle values”. Their intensities are therefore smaller than the intensities of the white areas and larger than the intensities of the black areas. Ge & Wunderlich [27] use fixed thresholds to classify the middle intensities. However, as these change greatly depending on the current scan situation, the algorithm is extended by an automatic threshold setting. Using the k-mean algorithm, the intensities are clustered into “white” and “black”. Intensities that do not belong to any of the two clusters lie in between and are assumed to be points on the edges.
3. **Line fitting:** Analogous to the algorithm using image gradients, two lines are estimated through the points of the edges from step 2. Again, the RANSAC algorithm first estimates which points belong to which line. Subsequently, the two final lines g_1 and g_2 are estimated through these points with the help of a least squares adjustment.
4. **Final coordinate calculation:** Same procedure as for the algorithm using image gradients, see Section 3.1.1.

3.2. Empirical Comparison of the Different Algorithms

In order to validate the performance of each algorithm, targets are scanned multiple times as described in Section 3.2.1. Afterwards, the precision of the TCE is estimated for each algorithm in Section 3.2.2. The results are analyzed in Section 3.2.3.

3.2.1. Experimental Setup

To investigate the different algorithms empirically, ten Leica Tilt&Turn targets are scanned eight times by means of the laser scanner Leica ScanStation P20 with an angular resolution setting of 0.8 mm at 10 m. In order to also consider different scan geometries, the targets are scanned at nine distances

between 2 m and 100 m. A schematic drawing of the experimental setup and an exemplary point cloud can be seen in Figures 4 and 5, respectively.

Figure 4. Schematic drawing of the experimental setup for the investigation of the algorithms' precisions.

Figure 5. Exemplary point cloud of the ten scanned Leica Tilt&Turn-Target for the investigation of the algorithms' precisions.

3.2.2. Methodology for Evaluation

For each distance d and each of the eight repetitions k , the coordinates $x = [r, h, v]^T$ of all targets t are determined by means of the manufacturer software Cyclone, the algorithm using image gradients, the algorithm using image correlations and the algorithm using middle intensities. Here, r equals the distance, h the horizontal direction, and v the zenith angle.

When the coordinates of the eight repetitions are examined more closely, it is evident that the coordinates shift systematically with each repetition. Since all ten targets showed similar movements, an analysis of variance (ANOVA) was performed confirming that the movement of the targets was significantly related to a movement of the scanner between the repetitions. The reasons for the scanner movement may possibly be thermal effects or torques, but its analysis is not the focus of this study. If standard deviations of the eight repetitions were calculated, these would be biased because of the systematic movement of the scanner. Therefore, coordinate differences of two adjacent targets t and $t + 1$ are calculated with

$$\Delta x([t, t + 1], k, d, a) = x(t + 1, k, d, a) - x(t, k, d, a) = \begin{bmatrix} \Delta r([t, t + 1], k, d, a) \\ \Delta h([t, t + 1], k, d, a) \\ \Delta v([t, t + 1], k, d, a) \end{bmatrix} \quad (1)$$

for each repetition k , each distance d , and each algorithm a . From the ten coordinate differences of the repetitions, it is now possible to calculate standard deviations of the differences $\hat{\sigma}_{\Delta r}([t, t + 1], d, a)$, $\hat{\sigma}_{\Delta h}([t, t + 1], d, a)$, and $\hat{\sigma}_{\Delta v}([t, t + 1], d, a)$ for which the systematic movements of the scanner have no influence. This procedure is necessary here, since the precision of the TCE is to be investigated independently of the systematic effects of a laser scanner.

Since the standard deviation increases by a factor of $\sqrt{2}$ due to the calculation of differences, the standard deviation of a single TCE can also be calculated from the standard deviation of the coordinate differences using the following formula

$$\hat{\sigma}_r(t, d, a) = \hat{\sigma}_{\Delta r}([t, t + 1], d, a) / \sqrt{2}, \quad (2)$$

$$\hat{\sigma}_h(t, d, a) = \hat{\sigma}_{\Delta h}([t, t + 1], d, a) / \sqrt{2}, \quad (3)$$

$$\hat{\sigma}_v(t, d, a) = \hat{\sigma}_{\Delta v}([t, t + 1], d, a) / \sqrt{2}. \quad (4)$$

As the standard deviations of the different targets t hardly differ, they can be averaged to the standard deviations $\hat{\sigma}_r(d, a)$, $\hat{\sigma}_h(d, a)$, and $\hat{\sigma}_v(d, a)$. Since the standard deviations of the horizontal direction $\hat{\sigma}_r(d, a)$ and the zenith angle $\hat{\sigma}_v(d, a)$ also show hardly any differences, these are averaged to a standard deviation $\hat{\sigma}_w(d, a)$ of the angles w .

As results of this data processing, standard deviations $\hat{\sigma}_r(d, a)$ and $\hat{\sigma}_w(d, a)$ for each of the four algorithms a depending on the distance d are obtained.

3.2.3. Analysis of the Algorithms' Precisions

The calculated standard deviations are visualised in Figure 6 and listed in Table 2. The Figure shows that the standard deviations of the distance $\hat{\sigma}_r$ do not differ significantly across the different algorithms (Figure 6, left). Up to a scan distance of 20 m they are in the lower sub-millimetre range and rise to a few millimetres at 100 m scan distance. Since the targets are approximately aligned to the scanner, the standard deviation in distance direction is determined by the precision of the plane estimation. As all three algorithms perform a least squares adjustment for the plane estimation, hardly any differences between the three algorithms are recognizable. The small differences come either from the random part of the RANSAC plane estimation in the first step of the algorithms or from the errors in angular direction, which indirectly affect the distance error when the targets are not exactly aligned orthogonally to the scanner.

Figure 6. Empirical standard deviations in distance direction $\hat{\sigma}_r$ and angular direction $\hat{\sigma}_w$ for each algorithm depending on the distance.

Table 2. Empirical standard deviations in distance direction $\hat{\sigma}_r$ and angular direction $\hat{\sigma}_w$ for each algorithm (Cyc.: Cyclone, im.grad.: image gradients, im.corr.: image correlations, mi.int.: middle intensities).

Scan Distance [m]	$\sigma_{r,Cyc.}$ [mm]	$\sigma_{w,Cyc.}$ ["]	$\sigma_{r,im.grad.}$ [mm]	$\sigma_{w,im.grad.}$ ["]	$\sigma_{r,im.corr.}$ [mm]	$\sigma_{w,im.corr.}$ ["]	$\sigma_{r,mi.int.}$ [mm]	$\sigma_{w,mi.int.}$ ["]
2	0.30	42.8	0.03	3.0	0.02	0.4	0.06	4.8
5	0.15	11.3	0.03	2.5	0.02	0.3	0.02	1.8
10	0.11	3.2	0.05	1.1	0.03	0.2	0.05	1.3
15	0.09	1.3	0.07	0.9	0.05	0.2	0.06	0.8
20	0.10	0.9	0.09	0.9	0.07	0.2	0.09	0.8
35	0.27	1.4	0.28	1.6	0.26	0.6	0.34	1.5
50	0.57	2.1	0.70	2.4	0.39	0.8	0.46	1.9
75	2.41	4.1	0.93	4.4	1.00	0.9	1.35	3.0
100	3.77	8.0	—	—	2.43	0.9	2.42	4.4

The standard deviations in angular direction $\hat{\sigma}_w$ show significant differences between the different algorithms (Figure 6, right). The precision of the TCE by manufacturer software is similar to the precision of the algorithms using image gradients and middle intensities. The algorithm using image correlations, however, provides significantly smaller standard deviations $\hat{\sigma}_w$. Both in the close range up to 20 m and in the medium range up to 100 m, the algorithm using image correlations, with a standard deviation of about 1 arcsec, is clearly superior to the other algorithms, with standard deviations of several arc seconds. The effect of this superiority becomes apparent when the angular standard deviations are converted from arc seconds into millimeters. Here, the standard deviation of the distance is slightly larger than half a millimeter at a scan distance of 100 m. Furthermore, it should be noted that the curves in angular direction $\hat{\sigma}_w$ are calculated from the mean of $\hat{\sigma}_h$ and $\hat{\sigma}_v$ and are thus smoother than the curves of $\hat{\sigma}_r$ for which no mean calculation is performed.

For the TCE using manufacturer software (here Leica Cyclone), the standard deviations are in the submillimeter range for distances up to 20 m and thus well below the accuracy of 2 mm specified by the manufacturer [43]. For longer scan distances of up to 100 m, the standard deviations increase to a few millimeters. However, it should be noted that the manufacturer recommends the TCE only for distances up to 50 m.

In summary, three things can be stated:

- The precision of the TCE is significantly higher than generally expected and specified by the manufacturer. In the close range (up to 20 m), the standard deviations are all in the submillimetre range and, for longer distances (up to 100 m), they equal a few millimetres.
- For the precision in distance direction it is irrelevant which algorithm is used for the TCE, except for the manufacturer software Leica Cyclone.
- Contrastingly, the algorithms differ significantly in their angular precision. Here, the algorithm using image correlations achieves the best results with a standard deviation of just slightly more than 1 arcsec over the entire measuring range.

4. Influence of the Target Design on the Uncertainty of the Target Center Estimation

Section 4.1 focuses on preliminary considerations for possible target designs. Section 4.2 empirically investigates the precision of different target designs, available from manufacturers and laser scanning shops. In Section 4.3, the findings are used to design a new target and compare this with the previous ones.

4.1. Preliminary Considerations of Target Designs

Besides the geometric description, the properties color, material, surface finish, and reflectivity are used to describe the target designs in previous literature [25,44,45]. They are briefly explained in the following:

Geometry: In the geometric form of targets, a differentiation is made between plane and spatial targets. Spatial targets, e.g., spheres, can signal a reference point only by their geometric shape. For plane targets, radiometric information (intensities) have to be used to determine the reference point in the plane. However, because of the “squishing” and “flaring” effect [23,25], mentioned in Section 2, only plane targets are considered in the following.

Material: The material of the target usually refers to the substrate material. Depending on the material (and wavelength of the laser), the laser beam penetrates the material to different depths. This can lead to systematic errors in the distance measurements. According to Muralikrishnan et al. [24], the materials aluminium and wood have the smallest errors and thus seem to be the most suitable materials for targets. The use of synthetic materials, such as plastic, should be avoided following the studies by Reshetyuk [21] and Rachakonda et al. [25]. The material, together with the surface finish and color, defines the reflectivity of a target.

Surface finish: Surface finish refers to the physical property of the target surface (border material to the atmosphere). It is defined by the roughness of the surface and is decisively responsible for the type of reflection (diffuse or reflective). According to Gordon et al. [46] and Rachakonda et al. [23], diffuse surfaces provide the most precise measurement results. The surface finish can be influenced by treatments such as sandblasting or painting. Muralikrishnan et al. [24] say that sandblasting aluminium results in a scan-friendly, matt, grey surface. The surface finish also influences the reflectivity of a target.

Color: The surface color of the target affects the reflected intensities [19,47] and thus the random errors of the distance measurement [48]. When plane targets are used, the color must not only lead to a precise geometric measurement of the target, but also make it possible to determine the target coordinates on the basis of radiometric information. This means that the color of the pattern must have a sufficiently high intensity contrast to enable an exact TCE (see Section 3). Therefore, the colors white and black are frequently selected.

Reflectivity: The reflectivity is the quotient of reflected and injected intensity. The aforementioned properties (material, surface finish, and color) influence the reflectivity of targets. This, in turn, affects the quality of the distance measurement and the scanned intensities. A high reflectivity leads to higher intensities and thus to more precise distance measurements [19,48]. This is helpful for the exact geometric detection of targets. It should be noted that the reflectivity is a physical property of the target [19].

Pattern: When using plane targets, the coordinates on the planes are estimated using the radiometric information (intensities) of the point cloud. The target center is signalled with the help of a colored pattern. For almost all commercial targets, the checkerboard pattern is used. Omidiazarandi et al. [38] show that, in image assisted total stations, other target patterns lead to more precise results. It is not known to what extent a different target pattern improves the precision of the target center coordinates in TLS. Therefore, this influence is investigated in Section 4.3.

4.2. Empirical Investigations

In order to investigate the precision of the different target designs, an experimental setup analogous to the investigation of the different algorithms is chosen (Section 3.2). In this case, different realizations of targets are scanned. From the repetitions, a standard deviation of the TCE is calculated for each investigated target design. Section 4.2.1 describes the experimental setup in detail. Section 4.2.2 explains the methodology used to evaluate the experimental data. In Section 4.2.3 the data is analyzed with regard to the influence of the target design and the scan geometry on the precision of the TCE.

4.2.1. Experimental Setup

In order to quantify the influence of the target design, five different existing targets are investigated. The investigated targets are a target printed on paper *t1*, a target from print house Schwerte *t2*, a Leica Tilt&Turn target *t3*, a target from Laserscanning Europe *t4*, and a close-range target from the Leibniz

University Hannover *t5*. These targets differ in size, material, surface finish, color, and reflectivity. Table 3 provides an overview of the designs of the respective targets, where the entries for surface finish, color, and reflectivity were created from subjective evaluations. Table 3 also lists the target *t6* from the University of Bonn, which will be introduced in Section 4.3.

Table 3. Characteristics of the five tested target designs (*t1*–*t5*, Section 4.2) and of the newly developed target (*t6*, Section 4.3).

No.	Dealer	Geometry	Material	Surface Finish	Color	Reflectivity
<i>t1</i>	self-printed	round Ø 20 cm	Paper (fixed on wood)	rough	black/white	diffuse
<i>t2</i>	print house Schwerte	square 40 × 40 cm	aluminium composite	medium	black/white	medium
<i>t3</i>	Leica Geo- systems	round Ø 15 cm	metal	rough	grey/white	diffuse
<i>t4</i>	Laserscanning Europe	square 20 × 20 cm	aluminium composite	medium	grey/white	medium
<i>t5</i>	Leibniz University Hannover	square 15 × 15 cm	aluminium composite	slick	black/white	glossy
<i>t6</i>	University of Bonn	square 30 × 30 cm	aluminium composite	rough	black/white	diffuse

The targets are scanned with the Leica ScanStation P20 and an angular resolution setting of 0.8 mm at 10 m. Quantifying the influence of the scan geometry, the targets are measured at distances of 5 m, 10 m, 15 m, 20 m, 35 m, 50 m, 75 m, and 100 m and with incidence angles of 15°, 30°, 45°, and 60°. The scans from 5 m to 20 m were captured in the basement of the Institute for Geodesy and Geoinformation at the University of Bonn (Figure 7, left), the data from 35 m to 100 m was scanned in the basement of the Faculty of Civil, Geo and Environmental Engineering at the Technical University of Munich (Figure 7, right). In order to be able to exclude and eliminate systematic errors in the evaluation (see Section 4.2.2), two targets of each target type were scanned.

The incidence angles were checked with a total station. It turned out that the incidence angles were set within a tolerance of 3° referring to the orientation of the targets to the scanner. The precision of the TCE at an incidence angle of 0° was not investigated because small incidence angles result in systematic errors due to total reflection [49]. Since the magnitude of these errors strongly depends on how exactly the incidence angle of 0° (here: 3°) has been set, only the errors from the imperfect execution of the experiment would have resulted here.

Figure 7. Photos of the experimental setup in the basements of the University of Bonn (left) and of the Technical University of Munich (right).

For all combinations of target, scan distance and incidence angle, ten repeat scans were recorded to calculate a standard deviation of the TCE. Figure 8 shows a schematic drawing of the experimental setup. The experiment has been repeated for different angular resolution settings up to 3.1 mm at 10 m and also with the scanners Leica BLK360, Leica HDS6100, and Faro Focus 3D X130. However, their results are not shown here because they did not provide new findings about the influence of the target design.

Figure 8. Schematic drawing of the experimental setup for the investigation of the target design's precision.

4.2.2. Methodology for Evaluation

The experimental setup described above produced 3200 point clouds of targets. For each scan, the coordinate of the target center is estimated using the image correlation algorithm. Analogous to Section 3.2.2, a transition to coordinate differences was done to eliminate systematic scan effects not related to the aim of these investigations. Since two realizations of each target design were scanned, standard deviations of the coordinate differences can be calculated for each target design. This precision of the coordinate differences is thus cleaned from systematic effects. From the standard deviation of the differences, the standard deviation of a single TCE can be calculated with the help of Equations (2)–(4).

As a result, the standard deviations $\hat{\sigma}_r(t, d, \beta)$ in distance direction and $\hat{\sigma}_w(t, d, \beta)$ in angular direction are obtained for each target design t depending on distance d and incidence angle β .

4.2.3. Analysis of the Influence of Target Designs

To analyze the impact of the target design on the TCE, the standard deviations $\hat{\sigma}_r$ and $\hat{\sigma}_w$ depending on the target t and distance d are investigated separately for each incidence angle β , as presented in Figure 9. Target t_6 will be discussed in Section 4.3.2. The Figure shows that the standard deviations of the five targets differ only slightly in their basic behaviour. In distance direction, the standard deviations are 0.1–0.2 mm up to a scan distance of 20 m and grow to a few millimetres up to a scan distance of 100 m. Starting at 35 m scan distance, targets t_3 and t_5 have higher standard deviations than the other targets. Target t_2 has one of the smallest standard deviations in most cases. These observations are related to the sizes of the targets, as targets t_3 and t_5 are the smallest targets tested with 15 cm and target t_2 is the largest target with 40 cm. Since the standard deviation in distance direction essentially depends on the plane estimation, this is reasonable: the more scan points on the target, the more precise the plane estimation is.

Figure 9. Standard deviations in distance direction $\hat{\sigma}_r$ and angular direction $\hat{\sigma}_w$ for different target designs: t_1 —target printed on paper, t_2 —target from print house Schwerte, t_3 —Leica Tilt&Turn target, t_4 —target from Laserscanning Europe, t_5 —a close-range target from the Leibniz University Hannover, t_6 —BOTA8 (see Section 4.3); targets scanned with Leica ScanStation P20 and a resolution of 0.8 mm at 10 m.

In angular direction, the differences in precision between the five targets are even smaller. Here, it can only be guessed that the targets t_2 and t_4 are in many cases the less precise targets. Figure 10 shows an enlargement of the area up to 25 m for an incidence angle of 15° . It can also be seen that targets t_2 and t_4 are less precise than the other three targets. This can be explained by the fact that the edges of the patterns are exactly horizontal or vertical. The scan points of the targets are also arranged in a vertical and horizontal grid, which may result in undefined areas. By rotating the pattern slightly, as with the targets t_1 , t_3 , and t_5 , these undefined areas can be reduced.

Figure 10. The standard deviations in angular direction $\hat{\sigma}_w$ for different target designs in the close range, targets scanned with Leica ScanStation P20 and a resolution of 0.8 mm at 10 m.

In general, it can be stated that the differences between the various targets are smaller than expected. For the precision in distance direction, the size of the target seems to play an important role for longer distances. For the angular precision, only the orientation of the pattern is suspected to have an influence. Further links between the target design and the precision of the TCE could not be established.

The influence of the scan geometry can also be analyzed from the recorded experimental data. As already shown, only small differences can be detected between the different target designs. In order to emphasize the influence of the scan geometry, the standard deviations $\hat{\sigma}_r(t, d, \beta)$ and $\hat{\sigma}_w(t, d, \beta)$ of the different designs t are averaged to standard deviations $\hat{\sigma}_r(d, \beta)$ and $\hat{\sigma}_w(d, \beta)$. Thus, these standard deviations only depend on the scan distance d , the incidence angle β and no longer on the target. The results are visualised in Figure 11.

Figure 11. Standard deviations in distance direction $\hat{\sigma}_r$ and angular direction $\hat{\sigma}_w$ for different incidence angles, targets scanned with Leica ScanStation P20 and a resolution of 0.8 mm at 10 m (calculated from data of targets $t1$ – $t5$).

As already noted from Figure 9 and now confirmed by Figure 11, the distance standard deviation increases with longer distances. The angular standard deviation decreases slightly up to a scan distance of 15 m and then also increases with longer distances. However, the decrease of the angular standard deviation in the close range can only be seen in the angular representation. When the angular standard deviations are converted into metric dimensions with their respective scan distance, the standard deviation is nearly constant up to 15 m and then increases with longer distance.

When comparing different incidence angles, it is observed that the larger the incidence angle, the larger the standard deviations $\hat{\sigma}_r$ and $\hat{\sigma}_w$. This link is particularly evident in distance direction. From the radar range equation [15], it is known that the intensities decrease with higher incidence angles and thus, according to Wujanz et al. [17], the standard deviations of the distance measurements increase. This corresponds with the results obtained here, whereby this link is determined for the first time for the precision of the TCE in this paper. Additionally, it can be observed that the angular standard deviation also increases with greater incidence angles. This is connected to the decreasing number of scan points on the target at greater incidence angles. The findings were confirmed by the evaluation of the data obtained with further scanners and resolution settings.

4.3. Improving the Target Design

The commercial targets investigated so far showed hardly any differences in their standard deviations of the TCE. Nevertheless, in the following Sections, it is attempted to achieve an increased precision of the TCE by means of an improved target design. Section 4.3.1 describes the conception of the new target. In Section 4.3.2, the benefit of the new targets is assessed on the basis of empirical studies.

4.3.1. Conception of the New Target (BOTA8)

Based on the result from Section 4.2.3 that the size of a target is an important factor for a small distance standard deviation, a size of 30 cm $\times$ 30 cm is chosen for the new target. This size appears to be a reasonable compromise between handiness, on the one hand, and a sufficiently large size for good precision, on the other. From theoretical considerations (Section 4.1) and further tests with different targets (not shown here), aluminium is chosen as material [24] and it is taken care that the surface appears as diffuse as possible [9].

Furthermore, different target patterns were tested in a simulation. They led to different correlation functions. In Figure 12, the simulated correlation functions of a classical checkerboard pattern are compared to a new 8-fold pattern (Figure 13). The correlation peak of the 8-fold pattern is spatially smaller and rounder than that of the checkerboard pattern. When the correlation functions are viewed along a profile of dy with $dx = 0$ and directly compared with each other, it can be seen that the correlation function of the 8-fold pattern is also steeper to the maximum than the checkerboard pattern. This steeper correlation function should increase the precision and robustness of the TCE.

An even smaller division of the fields to, e.g., an 16-fold pattern, was omitted, since fields smaller than a certain size cannot be resolved due to the angular resolution and the divergence of the laser beam (Section 2). The investigations of Omidalizarandi et al. [38] have shown that such an 8-fold pattern also provides the highest accuracy for image-assisted total stations.

Figure 12. Left and middle: simulated correlation functions depending on the shift $[dx, dy]$ for a checkerboard pattern and for an 8-fold pattern, right: direct comparison between the two simulated correlation functions depending on the shift dy .

When orienting the target pattern, the four white areas were placed in the corners of the target, so that they have a larger proportion than the black areas. Since white areas have a higher reflectivity, it is intended to further increase the precision in distance direction [17]. In order to use the full potential of the bigger white areas, the algorithm is modified so that it only estimates the plane of the target by the white points.

We call this newly developed target BOTA8 (BOnn TArget with 8-fold pattern). Figure 13 depicts an image and a point cloud of the BOTA8.

Figure 13. Left: photo of the newly developed target with 8-fold pattern (BOTA8, target t_6), right: scan of the BOTA8 (target t_6).

4.3.2. Benefit of the New Target (BOTA8)

The BOTA8 (t_6) was tested together with the other targets in the experiment described in Section 4.2.1 (Figure 7). The scans were evaluated using exactly the same methodology as described in Section 4.2.2. The standard deviations of the BOTA8 can thus be directly compared with the standard deviations of the previous target designs.

Figure 9 shows the standard deviations $\hat{\sigma}_r$ and $\hat{\sigma}_w$ of the BOTA8 (t_6) compared to those of the previous targets: In all tested scan geometries the new target design provides the smallest angular standard deviations. In some cases, the standard deviations in the distance direction are slightly above the standard deviations of target 2. However, this can be explained by the fact that target 2 is even larger than BOTA8 and the distance standard deviation depends mainly on the size of the target. With the Leica ScanStation P20 (angular resolution setting: 0.8 mm at 10 m) the standard deviation of the new target in distance direction is 0.5 mm at a scan distance of 100 m and an incidence angle of 15° . The standard deviation in angular direction is 1.2 arcsec. Although the differences to the other targets are too small to speak of a significant improvement, a visual analysis of the standard deviations from Figure 9 shows that the precision of the TCE could be improved by the BOTA8.

Finally, it is empirically checked whether the maximum of the correlation function becomes more unambiguous and steeper due to the new pattern of BOTA8 as expected from the simulation. Figure 14 shows the empirical correlation functions of the target t_1 and the BOTA8 (t_6) depending on the shift $[dx, dy]$ of the template within the target plane (scan distance: 50 m, incidence angle: 15°).

Figure 14. Left and middle: empirical correlation functions depending on the shift $[dx, dy]$ for the target t_1 and the BOTA8 (t_6), right: direct comparison between the two empirical correlation functions depending on the shift dy (scan distance: 50 m, incidence angle: 15°).

The basic conclusions of the simulation can be confirmed from the empirical data shown in Figure 14. However, the correlation values are slightly smaller than in the simulation. This is due to the effective spatial point density (Section 2): the coarser the point density gets, the more blurred the

intensity image becomes and the smaller the image correlations are. This will also be the reason why the new target is only slightly more precise than the existing ones.

5. Conclusions and Outlook

The present study examined the target center estimation (TCE) in all its aspects regarding its precision. Section 2 defines the influencing factors of the TCE based on the work of Soudarissanane et al. [10]: algorithm, laser scanner, scan geometry, and target design. In Section 3, different algorithmic approaches for the TCE were compared and evaluated for the first time. In Section 4, the influence of the target design on the TCE, which had never been investigated before, was empirically analyzed. Furthermore, an attempt was made to improve the precision of the TCE by means of the BOTA8. The contribution of this work can be summarized in the following four points, which at the same time answer the four questions of Section 1:

1. The calculated standard deviations of all algorithms are significantly smaller than the accuracies specified by the manufacturer and thus significantly smaller than generally assumed. For the TCE with the Leica ScanStation P20 and a resolution level of 0.8 mm at 10 m, standard deviations in the lower submillimeter range could be achieved for scan distances up to 20 m and standard deviations of a few millimeters for scan distances up to 100 m.
2. The algorithm applied has a large influence on the precision of the TCE. The algorithm using correlations provides significantly smaller standard deviations than the other tested algorithms, especially in angular direction.
3. The target design is of lesser importance for the precision of the TCE than assumed from theoretical considerations. The investigated target designs differ only slightly in their precision. However, it was observed that the size of the target is an important factor for the distance standard deviation.
4. The precision of the TCE was improved by a new target design, the BOTA8.

Further studies should investigate to what extent the improvements also affect the registration and calibration of laser scanners. Also, the movement of the target center coordinates during multiple scans has to be investigated in future studies.

Author Contributions: J.J. and C.H. conceived and designed the experiments; J.J. and T.M. performed the experiments; J.J., T.M., and C.H. analyzed the data; J.J. wrote the paper; H.K. provided the resources and gave specific input for the analysis. J.J., T.M., H.K., and C.H. read and improved the final manuscript.

Funding: This research received no external funding.

Acknowledgments: We thank Dr.-Ing. habil. Thomas Wunderlich and M.Sc. Wolfgang Wiedemann from the Technical University of Munich for providing us with the Leica ScanStation P20 for the long-range experimental procedure. We thank Hannes Frings for his support during the measurements.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Holst, C.; Klingbeil, L.; Esser, F.; Kuhlmann, H. Using point cloud comparisons for revealing deformations of natural and artificial objects. In Proceedings of the 7th International Conference on Engineering Surveying (INGEO 2017), Lisbon, Portugal, 18–20 October 2017; pp. 265–274.
2. Yang, H.; Omidalizand, M.; Xu, X.; Neumann, I. Terrestrial laser scanning technology for deformation monitoring and surface modeling of arch structures. *Compos. Struct.* **2017**, *169*, 173–179. [[CrossRef](#)]
3. Medić, T.; Holst, C.; Kuhlmann, H. Towards System Calibration of Panoramic Laser Scanners from a Single Station. *Sensors* **2017**, *17*, 1145. [[CrossRef](#)] [[PubMed](#)]
4. Muralikrishnan, B.; Ferrucci, M.; Sawyer, D.; Gerner, G.; Lee, V.; Blackburn, C.; Phillips, S.; Petrov, P.; Yakovlev, Y.; Astrelin, A.; et al. Volumetric performance evaluation of a laser scanner based on geometric error model. *Precis. Eng.* **2015**, *40*, 139–150. [[CrossRef](#)]
5. 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. *Meas. Sci. Technol.* **2014**, *25*, 105010. [[CrossRef](#)]

6. Menditto, A.; Patriarca, M.; Magnusson, B. Understanding the meaning of accuracy, trueness and precision. *Accredit. Qual. Assur.* **2007**, *12*, 45–47. [[CrossRef](#)]
7. Organización Internacional de Normalización (Ginebra). *ISO 5725-1 Accuracy (Trueness and Precision) of Measurement Methods and Results—Part 1: General Principles and Definitions*; ISO: Geneva, Switzerland, 1994.
8. Zogg, H.M. Investigations of High Precision Terrestrial Laser Scanning with Emphasis on the Development of a Robust Close-Range 3D-Laser Scanning System. Ph.D. Thesis, ETH Zurich, Zurich, Switzerland, 2008.
9. Soudarissanane, S. The Geometry of Terrestrial Laser Scanning; Identification of Errors, Modeling and Mitigation of Scanning Geometry. Ph.D. Thesis, TU Delft, Geoscience and Remote Sensing: Delft, The Netherlands, 2016.
10. Soudarissanane, S.; Lindenbergh, R.; Menenti, M.; Teunissen, P. Scanning geometry: Influencing factor on the quality of terrestrial laser scanning points. *ISPRS J. Photogramm. Remote Sens.* **2011**, *66*, 389–399. [[CrossRef](#)]
11. Lichti, D.D.; Chow, J.; Lahamy, H. Parameter de-correlation and model-identification in hybrid-style terrestrial laser scanner self-calibration. *ISPRS J. Photogramm. Remote Sens.* **2011**, *66*, 317–326. [[CrossRef](#)]
12. Boehler, W.; Vicent, M.B.; Marbs, A. Investigating laser scanner accuracy. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2003**, *34*, 696–701.
13. Lichti, D.D.; Jamtsho, S. Angular resolution of terrestrial laser scanners. *Photogramm. Rec.* **2006**, *21*, 141–160. [[CrossRef](#)]
14. Schaer, P.; Skaloud, J.; Landtwing, S.; Legat, K. Accuracy estimation for laser point cloud including scanning geometry. In Proceedings of the 5th International Symposium on Mobile Mapping Technology (MMT2007), Padua, Italy, 29–31 May 2007.
15. Jelalian, A.V. *Laser Radar Systems*; Artech House: Boston, MA, USA; London, UK, 1992.
16. Kaasalainen, S.; Ahokas, E.; Hyypä, J.; Suomalainen, J. Study of surface brightness from backscattered laser intensity: Calibration of laser data. *IEEE Geosci. Remote Sens. Lett.* **2005**, *2*, 255–259. [[CrossRef](#)]
17. Wujanz, D.; Holst, C.; Neitzel, F.; Kuhlmann, H.; Niemeier, W.; Schwieger, V. Survey Configuration for Terrestrial Laser Scanning. *AVN* **2016**, *6*, 158–169.
18. Schmitz, B.; Holst, C.; Medic, T.; Lichti, D.D.; Kuhlmann, H. How to Efficiently Determine the Range Precision of 3D Terrestrial Laser Scanners? *Sensors* **2019**, under review. [[CrossRef](#)]
19. Zámečníková, M.; Wieser, A.; Woschitz, H.; Ressler, C. Influence of surface reflectivity on reflectorless electronic distance measurement and terrestrial laser scanning. *J. Appl. Geod.* **2014**, *8*, 311–326.
20. Joeckel, R.; Stober, M.; Huep, W. *Elektronische Entfernungs- und Richtungsmessung und ihre Integration in aktuelle Positionierungsverfahren*; Wichmann Verlag: Berlin, Germany, 2008.
21. Reshetyuk, Y. Investigation of the influence of surface reflectance on the measurements with the terrestrial laser scanner Leica HDS 3000. *Z. Geod. Geoinf. Landmanag.* **2006**, *131*, 96–103.
22. Cheok, G.S.; Leigh, S.; Rukhin, A. *Calibration Experiments of a Laser Scanner*; NASA STI/Recon Technical Report N 2; 2002. Available online: <https://www.nist.gov/publications/calibration-experiments-laser-scanner> (accessed on 8 April 2019).
23. Rachakonda, P.; Muralikrishnan, B.; Cournoyer, L.; Cheok, G.S.; Lee, V.; Shilling, M.; Sawyer, D. Methods and considerations to determine sphere center from terrestrial laser scanner point cloud data. *Meas. Sci. Technol.* **2017**, *28*, 105001. [[CrossRef](#)] [[PubMed](#)]
24. Muralikrishnan, B.; Rachakonda, P.; Lee, V.; Shilling, M.; Sawyer, D.; Cheok, G.; Cournoyer, L. Relative range error evaluation of terrestrial laser scanners using a plate, a sphere, and a novel dual-sphere-plate target. *Measurement* **2017**, *111*, 60–68. [[CrossRef](#)] [[PubMed](#)]
25. Rachakonda, P.; Muralikrishnan, B.; Shilling, M.; Cheok, G.; Lee, V.; Blackburn, C.; Everett, D.; Sawyer, D. Targets for relative range error measurement of 3D imaging systems. *J. CMSC* **2017**, *12*. Available online: https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=923831 (accessed on 8 April 2019).
26. Chow, J.C.K.; Teskey, W.F.; Loves, J. In-situ Self-calibration of Terrestrial Laser Scanners and Deformation Analysis Using Both Signalized Targets and Intersection of Planes for Indoor Applications. In Proceedings of the 14th FIG Symposium on Deformation Measurements and Analysis, 5th IAG Symposium on Geodesy for Geotechnical and Structural Engineering, and 2nd International Workshop on Spatial Information Technologies for Monitoring the Deformation of Large-Scale Man-Made Linear Features, Hong Kong, China, 2–4 November 2011; pp. 2–16.

27. Ge, X.; Wunderlich, T. Target identification in terrestrial laser scanning. *Surv. Rev.* **2015**, *47*, 129–140. [CrossRef]
28. Kregar, K.; Grigillo, D.; Kogoj, D. High precision target center determination from a point cloud. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2013**, *II*, 139–144. [CrossRef]
29. Lichti, D.D.; Stewart, M.P.M.; Tsakiri, M.; Snow, A.J. Benchmark tests on a three-dimensional laser scanning system. *Geomat. Res. Aust.* **2000**, *72*, 1–23.
30. Gordon, S.; Lichti, D.; Stewart, M.; Tsakiri, M. Metric performance of a high-resolution laser scanner. *Proc. SPIE* **2001**, *4309*, 174–184.
31. Valanis, A.; Tsakiri, M. Automatic target identification for laser scanners. In Proceedings of the XXth ISPRS Congress, Istanbul, Turkey, 12–23 July 2004.
32. Eling, D. Terrestrisches Laserscanning für die Bauwerksüberwachung. Available online: https://www.dgk.badw.de/fileadmin/user_upload/Files/DGK/docs/c-641.pdf (accessed on 8 April 2019).
33. Chow, J.; Ebeling, A.; Teskey, B. Low cost artificial planar target measurement techniques for terrestrial laser scanning. In Proceedings of the FIG Congress 2010: Facing the Challenges—Building the Capacity. Citeseer, Sydney, Australia, 11–16 April 2010.
34. Rachakonda, P.; Muralikrishnan, B.; Sawyer, D.; Wang, L. Method to determine the center of contrast targets from terrestrial laser scanner data. In Proceedings of the 32nd ASPE Annual Meeting, Charlotte, NC, USA, 29 October–3 November 2017.
35. Abmayr, T.; Härtl, F.; Hirzinger, G.; Burschka, D.; Fröhlich, C. A correlation based target finder for terrestrial laser scanning. *J. Appl. Geod.* **2008**, *2*, 131–137. [CrossRef]
36. Liang, Y.B.; Zhan, Q.M.; Che, E.Z.; Chen, M.W.; Zhang, D.L. Automatic registration of terrestrial laser scanning data using precisely located artificial planar targets. *IEEE Geosci. Remote Sens. Lett.* **2014**, *11*, 69–73. [CrossRef]
37. Yi, C.; Xing, H.; Wu, Q.; Zhang, Y.; Wei, M.; Wang, B.; Zhou, L. Automatic Detection of Cross-Shaped Targets for Laser Scan Registration. *IEEE Access* **2018**, *6*, 8483–8500. [CrossRef]
38. Omidalizarandi, M.; Paffenholz, J.A.; Neumann, I. Automatic and accurate passive target centroid detection for applications in engineering geodesy. *Surv. Rev.* **2018**, 1–16. [CrossRef]
39. Fischler, M.A.; Bolles, R.C. Random Sample Consensus: A Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography. *Commun. ACM* **1981**, *24*, 381–395. [CrossRef]
40. Mikhail, E.M.; Ackerman, F. *Observations and Least Squares*, 1st ed.; IEP: New York, NY, USA, 1976.
41. Canny, J. A computational approach to edge detection. *IEEE Trans. Pattern Anal. Mach. Intell.* **1986**, *6*, 679–698. [CrossRef]
42. Guizar-Sicairos, M.; Thurman, S.T.; Fienup, J.R. Efficient subpixel image registration algorithms. *Opt. Lett.* **2008**, *33*, 156–158. [CrossRef]
43. Leica Geosystems. Data Sheet for Leica ScanStation P20. 2013. Available online: www.leica-geosystems.com (accessed on 4 February 2019).
44. Lichti, D.; Brustle, S.; Franke, J. Self-calibration and analysis of the Surphaser 25HS 3D scanner. In Proceedings of the Strategic Integration of Surveying Services, FIG Working Week, Hong Kong, China, 13–17 May 2007; Volume 1317.
45. Muralikrishnan, B.; Rachakonda, P.; Shilling, M.; Lee, V.; Blackburn, C.; Sawyer, D. *Report on the May 2016 ASTM E57.02 Instrument Runoff at NIST, Part 1—Background Information and Key Findings*; Technical Report, NISTIR 8152; US Department of Commerce, National Institute of Standards and Technology: Gaithersburg, MD, USA, 2016. [CrossRef]
46. Gordon, S.; Davies, N.; Keighley, D.; Lichti, D.; Franke, J. A rigorous rangefinder calibration method for terrestrial laser scanners. *J. Spat. Sci.* **2005**, *50*, 91–96. [CrossRef]
47. Kersten, T.P.; Sternberg, H.; Mechelke, K. Investigations into the accuracy behaviour of the terrestrial laser scanning system Mensi GS100. In Proceedings of the Optical 3D Measurement Techniques VII, Vienna, Austria, 3–5 October 2005; Volume 1, pp. 122–131.

48. Wujanz, D.; Burger, M.; Mettenleiter, M.; Neitzel, F. An intensity-based stochastic model for terrestrial laser scanners. *ISPRS J. Photogramm. Remote Sens.* **2017**, *125*, 146–155. [[CrossRef](#)]
49. Tan, K.; Cheng, X. Specular Reflection Effects Elimination in Terrestrial Laser Scanning Intensity Data Using Phong Model. *Remote Sens.* **2017**, *9*, 853. [[CrossRef](#)]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).