Some Remarks on Registration Techniques of Point Clouds Obtained from Terrestrial Laser Scanning

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Abstract. Terrestrial laser scanning (TLS) is a measurement technique used for many geodetic applications (such as determination of displacement and deformation of building objects or monitoring of engineering structures) as well as for non-geodetic applications (for example in forestry, archeology or geotechnics). Despite the high level of automation, the measurement with a laser scanner and the processing of the results consist of many stages and depend on many factors. The most important factors are: the features of measurement object (size, material, availability), required accuracy, speed of scanning, required scan density, type of reference frame, registration method, planned visualization, and 3D modelling method. In this article, the authors focused on the type of registration technique of point clouds obtained from TLS. The most popular strategies of registration were discussed. The practical application of the selected technique was presented on the example of measurement of the railway gauge of the viaduct. Due to the characteristic object (narrow and long railway line) and considering the local reference frame of point clouds as well as the need of minimization of the measurement time, the hybrid registration method in the nested variant was selected.

1. Introduction
Terrestrial laser scanning (TLS) is a measurement technique for acquiring three-dimensional (3D) information about the geometrical shape of an object. Due to the noncontact, fast and accurate measurement, laser scanning has in recent years been an alternative to classical geodetic measurements [1]. The measuring principle in terrestrial laser scanning is based on measuring the distance and angles to an object using a laser beam [2].

In the literature, there are several methods of classification of terrestrial laser scanners. In work [3], the authors classify TLS depending on the distance measurement method and available technical parameters, such as: scanning speed, field of observation, laser operating frequency, laser beam deflection methods, spatial resolution, or integration with other devices installed on a laser scanner. The most popular categorization due to the distance measurement technology used is divided into: pulsed-time of flight (ToF) scanners, phase-based (continuous wave) scanners, and triangulation-based scanners, as shown in figure 1.
Figure 1. Methods of distance measurement in laser scanners.

Pulsed - time of flight (ToF) scanners determine the distance based on the direct measurement of time of the laser beam between the emitter and the receiver object. The distance $d$ can be determined by the following formula [4]:

$$d = \frac{c \cdot t}{2}$$  \hspace{1cm} (1)

where:
- $c$ – speed of light in the medium,
- $t$ – the time between the sending of the laser beam and the moment of its return after reflection from the scanned object.

In phase-based scanners, the distance measurement is based on continuous waves of laser beam intensity, which, emitted by the scanner detector, reflect from the object and return with a specified time delay [4]. The distance $d$ is obtained from the formula:

$$d = \frac{1}{4\pi} \cdot \frac{c}{f} \cdot \varphi$$  \hspace{1cm} (2)

where:
- $c$ – speed of light in the medium,
- $f$ – wave frequency,
- $\varphi$ – wave phase.

In triangulation-based scanners, distance measurement is based on functional dependencies in a triangle, in accordance with the principle of triangulation. Knowing the distance between the laser emitter and the camera (called base) and the angle between the base line and the laser beam, the distance from the object to the scanning system can be calculated [5].

The technology used for distance determination also affects the range, accuracy, and application area of laser scanners (Table 1).

Table 1. Classification of laser scanners in terms of range, accuracy, and potential applications [6].

| Distance measurement technology | Measurement range [m] | Mean error of single point measurement [mm] | Applications |
|-------------------------------|-----------------------|-------------------------------------------|--------------|
| pulsed - time of flight       | < 1000                | < 20                                      | deformation monitoring, mining, land slide monitoring, topography surveying, glaciology monitoring, civil engineering, reverse engineering, forestry assessment, cultural heritage machine industry, medicine, forensic, quality assessment |
| phase-based                   | < 300                 | < 3                                       |              |
| triangulation-based           | < 5                   | < 1                                       |              |
The TLS is mainly used in research on displacement and deformation measurements, which is presented in the papers [7, 8]. The study of deformation of objects includes various types of geometrically complex engineering structures, in particular dams [9, 10], bridges [11, 12], tunnels [13, 14], and many others. Moreover, the TLS technology is applicable in archeology [15], forestry [16,17], and geomorphology [18, 19].

2. Methods
A typical course of work during the performance of terrestrial laser scanning is shown in figure 2. At the stage of preparing the measurement, the following features of the object should be analysed: the size, availability, and properties of the object’s material (type of paint coating, colour, roughness, moisture, contamination or corrosion of the surface). Black paint coatings and contaminations absorb a large part of the laser signal and shorten the effective working range of the scanner. Smooth and shiny surfaces cause regular reflection and only the residual part of laser signal returns to the scanner. Such the signal is below a given quality threshold and is usually cut off, which results in a missing point in the point cloud. Moisture can also make measurement impossible for some types of laser scanners. The dimensions of the object and the possible location of the scanner positions dictate the required scanner working range. The above-mentioned features, together with the required accuracy, speed of scanning, and required scan density, determine the choice of a specific scanner model. Depending on the purpose of laser scanning, a reference frame should be selected in which point cloud will be developed. For visualization and modelling purposes, a local coordinate system is usually assumed, which is the most convenient solution. However, if it is necessary to place the 3D model on the map in a fixed, usually national coordinate system, the geodetic control points must be known and used. A similar situation occurs in the case of using laser scanning for the determination of displacements and deformations of building objects. The comparison of point clouds from two different measurement epochs requires the maintenance of the same specific reference system, which must be materialised (stabilized) in a proper manner.

![Figure 2. Terrestrial laser scanning – the typical work stages.](image-url)
Field work usually begins with a field reconnaissance, when the convenient positions of the scanner are planned. The basic assumption is to maximize the field of view of the scanner, ensure favourable angles of incidence of the laser beam, and minimize the inevitable obstructions (obstacles) resulting in voids in the point cloud. At this stage, the desirable reference frame and intended type of point cloud registration have to be known (figure 3). If it is necessary to link the point cloud with the existing reference system and/or to perform registration with the use of targets, the establishment of a geodetic control network is essential. Sometimes such the network is measured with high-precision electronic total stations and the control points get the known 3D coordinates. At each scanner position, at least four targets (known points or only tie-points) should be visible. In the case of cloud-to-cloud registration, it is necessary to obtain a large overlap of areas scanned from adjacent scanner positions. New models of laser scanners, simultaneously with data acquisition, perform preliminary registration of point clouds from subsequent scanner positions. It enables better field control of the acquired data and speeds up the subsequent data processing, however, it increases energy consumption and shortens the scanner operation time (battery powered).

![Figure 3. Typical strategies of point clouds registration in engineering applications.](image)

The order of the postprocessing steps may vary slightly depending on the specific scanner model and the planned method of registration. When using targets for registration, the postprocessing usually begins with an inspection of the correctness of automatic detection of central points of planar targets or spheres. More advanced scanners enable the point cloud filtration based on parameters describing the quality and physical properties of the reflected laser signal (e.g., reflectance, intensity, amplitude, standard deviation, return number). It allows to remove a significant part of the measurement noise and points representing false reflections from the edges of the measured object.

The process of point clouds registration obtained from individual scanner positions is crucial for the accuracy of subsequent 3D modelling. Figure 3 presents three typical approaches: 1) target-based registration; 2) cloud-to-cloud registration; and 3) hybrid registration combining the two previous ones.

- Target-based approach is older and refers to the principles of classical geodetic surveying. Usually, the scanner had to be levelled on its position, which ensured the verticality of the main axis of instrument rotation. This solution simplifies the registration process, reducing it to the
calculation of translation parameters and rotation around one vertical axis (with a calibrated rangefinder, the scaling problem does not occur). One should be mentioned that in unstable ground or on offshore oil platforms, the scanner compensator must be turned off and the vertical axis of the instrument cannot be realized. As mentioned earlier, the target-based registration requires to establish a geodetic network and materialize the tie-points. Although the measurement of the tie-points took a long time, the acquired data set was not large, as it was limited only to the object of interest (without surroundings). An investigation of the spatial pattern and the magnitude of the actual registration and georeferencing errors in TLS data is presented in [20]. The process of designing and implementing of an innovative target which would be suitable for accurately registering the point clouds is described in [21]. A novel automatic and accurate passive target centroid detection approach is proposed in [22].

- The increase of scanning speed in newer scanner models has developed an approach based on the mutual matching of point clouds during the registration process. The scanner does not need to be levelled, which significantly speeds up the setting up of the scanner position. The instrument's orientation in space is recorded by means of an internal inertial unit. This entails the need to apply a full three-dimensional transformation in the process of point clouds combining from individual scanner stations. The matching of point clouds is most often performed using the iterative closest point (ICP) algorithm developed by [23] and [24]. A literature review on surface matching techniques used in the point clouds registration is included in [25]. Searching for a large number of planar patches increases the efficiency of the registration process, but at the same time requires a greater number of scanner positions and scanning the surroundings, which significantly increases the amount of data processed.

- The most optimal solution is a hybrid approach in the variant of simultaneous use of targets and matching of point clouds. Depending on the number of targets used and the accuracy of their coordinates, weights are assigned to define the confidence level of the tie-points in relation to the fit based on the surface matching. A significant limitation of the effectiveness of surface matching are too small common areas on adjacent scans and/or large voids caused by obstacles. In the case of significant quality differentiation between the acquired point clouds (dense, with large common areas) and the coordinates of the tie-points (low accuracy, but an external reference frame is required), a hybrid approach in the nested variant is recommended. Then, a local registration and mutual alignment of point clouds are applied first, and then all combined point clouds are transformed to the required reference system as a rigid body (georeferencing).

The last part of the postprocessing stage is cropping of the scanned area and modelling of point cloud (usually in dedicated software) to obtain a 3D model of the scanned object in the required file format.

3. Results and discussions

3.1. Research facility

The research object was a road viaduct over an active railway line (figure 4) located in the south-western part of Poland. The purpose of the measurement was to examine the railway gauge of the viaduct. After analyzing the specifics of the object (a long and narrow railway line, limited on both sides by high walls, consisting of two tracks with frequent train journeys on one track), the Riegl VZ-400i impulse scanner was used for measurement. The resulting point cloud should be expressed in the local reference frame parallel to the axis of the track under the viaduct. The axis of the track had to be reconstructed on the basis of measurements with a total station. An additional limitation was the minimization of the time spent by employees on the tracks. The above factors determined the use of the hybrid registration method in the nested variant.
3.2. Field works

After a field reconnaissance, a geodetic network consisting of 23 points was established (figure 5). Points no. A, B, C were positions of the total station, points no. 1-17 were reflective sheet targets glued on the object, and points no. 1001-1003 were directional points stabilized with metal bolts outside the railway. The angular linear measurements were made in two series, in two positions (faces) of the telescope by means of Trimble S7 robotic total stations. Additionally, points no. Sz3-Sz10 (not visible in figure 5) representing the inner edges of the rails of both tracks were measured in two cross-sections located in front of and behind the viaduct.

Measurements with a laser scanner were made from 14 positions of the instrument located along track 2. At each position, the readings of the inertial measurement unit (IMU) and GNSS antenna were determined and a panoramic scan with a resolution of 20 mdeg and a sampling frequency of 1200 Hz were performed. Additionally, a series of photos for colouring the cloud of points were taken. At each scanner position, the tie-points signalled by white reflective targets were additionally scanned.

3.3. Postprocessing works

Observations of angles and distances were 3D adjusted using the least squares method in a pseudo-free manner (assuming known coordinates of point B and known azimuth from B to C). The mean square error of the horizontal position of the points after adjustment was 0.0018 m. On the basis of the measured points on the edges of the rails, the position of the axis of the track no. 1 (represented by points O3-O4) and the position of the axis of the track no. 2 (represented by points O1-O2) were calculated (figure 5). Then the position of the track axis represented by points O5 and O6 was calculated. As the desired local coordinate system should be parallel to the track axis O5-O6, in the next stage, an isometric

![Figure 4. View of the viaduct: (a) measurement with the Trimble S7 robotic total station; (b) measurement with a Riegl VZ-400i pulse laser scanner and a small reflective sheet target in a red circle visible on the right wall.](image)
transformation of coordinates was performed without changing the scale using the Helmert method. As a result, the final coordinates of the measurement network points (reflective sheet targets) were obtained.

Figure 5. Scheme of the geodetic network: a general view and an enlarged fragment.

The data from the laser scanner were first cleaned of isolated points and filtered by the following parameters: reflectance and deviation. Next, the mutual alignment of point clouds from each scanner position was performed (Multi-Station Adjustment). Then, all point clouds (as a rigid body) were fitted
into desired coordinate system established from total station measurements on the basis of known coordinates of reflective sheet targets. The error of fitting was 0.0029 m. In the next step, the point cloud density was unified to the value of 3 mm. The development of the point clouds was performed in the RiscanPro software. At the end, several cross-sections were cut from the point cloud, which were used for the analysis of the viaduct gauge.

3.4. Discussion

The geometry of the measured object was rather unfavourable due to the long and narrow shape of the railway line. Nevertheless, the large number of densely spaced scanner positions ensured good point cloud coverage at adjacent scanner positions. Precise tacheometric measurements allowed to obtain high accuracy of coordinates and recreate the required reference frame related to the track axis under the viaduct. Potentially, it would be possible to use a different registration approach, but it would extend the time of field measurements performed with a scanner in a dangerous place.

4. Conclusions

Terrestrial laser scanning is a modern, still developing measurement technique used for various engineering issues. In addition to the proper selection of measurement methods and the selection of the optimal data processing strategy, the key data in the processing point clouds is the registration. In the literature, there are various methods of point clouds registration which are constantly being improved. Especially in the field of automation of the registration process, the collaboration of researchers from the fields of science such as computer vision and artificial intelligence is noticeable. This paper presents a hybrid registration technique for an unusual object, such as a railway tunnel. This topic can be developed further via verification of registration techniques known from the literature on a larger number of real engineering structures.

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