TLS Point Cloud Registration

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Content

1 Introduction

Anyone can generate three-dimensional (3D) data these days. The handling and operation of measuring instruments in the laser scanning sector have become increasingly simplified. However, this should not obscure the complexity and sophistication of the processing of the point clouds generated.

Many accuracy measures of point clouds often only take into account manufacturer-specific information on angle and distance measurement in terrestrial laser scanning (TLS). At best, this approach is applicable when considering a single laser scan. In this case, the uncertainty budget includes only components caused by the laser scanner itself. Multiple laser scanner positions are required for a complete acquisition of objects in most applications. Here, the uncertainty budget is increased by the influence of the so-called registration, in which transformation parameters are calculated between the individual scans and transferred into a common coordinate system. Unfortunately, registration is often treated nowadays as a trivial matter that does not require in-depth knowledge.

This guide is intended to provide assistance to users in answering key questions related to the registration of point clouds. These include:

- What is registration?
- What are the registration methods?
- Which registration processes are suitable in which cases?
- What needs to be considered during the scan acquisition?
- How does the registration affect the accuracy of the point clouds generated?

Different aspects around the registration of TLS point clouds are discussed in this guide. The explanations are limited to the registration of statically acquired laser scans. It does not deal with the processing of point clouds acquired in kinematic laser scanning. The guide is aimed at both users experienced in TLS and people who are not yet very familiar with the TLS topic.

The following remarks are first devoted to basic explanations and considerations of registration, its accuracy, and the elementary prerequisites and challenges. Subsequently, different steps, methods and algorithms of registration procedures are treated. In order to be able to evaluate the results, possibilities of an accuracy or quality assessment are additionally presented.

Finally, best practice tips provide valuable assistance for successful and good quality registration in practice.

2 What Is Registration?

Definition:

The registration is the determination of the six degrees of freedom to transform a point cloud from any local coordinate system into a common coordinate system (e.g. a project coordinate system).

Every scan performed with a terrestrial laser scanner is limited to its defined field of view. Therefore, several laser scanner positions are usually required to capture an object to be documented as completely as possible. Figure 1 shows a bust scanned from different positions. Each scan contains a different part of the object, depending on the laser scanner position. Since each scan takes place within an arbitrary local laser scanner coordinate system, so-called transformation or registration parameters must be calculated. These enable several scans to be transformed into a uniform coordinate system and, thus, generate a coherent set of data.

In addition, it may be useful to transfer the scans that have already been registered with each other into a superordinate coordinate system, for example, a reference system. This aspect will be discussed in more detail in section 7.5.

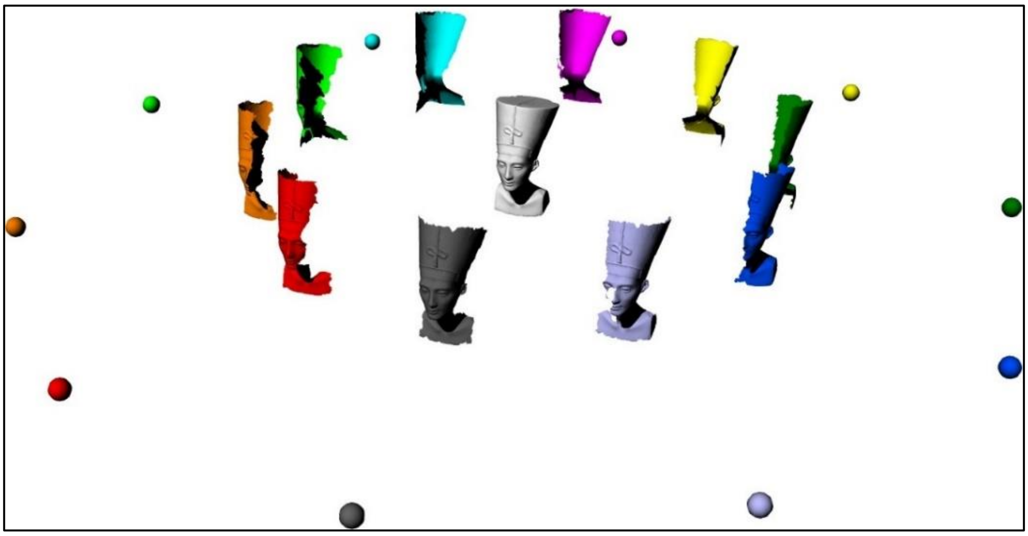


Figure 1: Object to be scanned (light grey), laser scanner positions (colored spheres) and resulting scans (colored triangulations) (Wujanz & Neitzel 2016)

Figuratively, a scan can be thought of as a (inherently rigid) piece of a puzzle. If registration parameters between scans are known, a point cloud can be transformed into the local coordinate system of another point cloud. A two-dimensional example is shown in Figure 2 in the form of a puzzle. The general goal of puzzling is to assemble an image that consists of individual pieces. This is comparable to individual point clouds of an object in TLS. To assemble the individual parts or point clouds, a single part can be rotated around the origin of its local coordinate system as well as shifted along X and Y. These three parameters are referred to as the "puzzle parameters" and also called degrees of freedom. Analogous to puzzling, registration is a sequential process in which the last scan is appended to the respective scan(s) already registered.

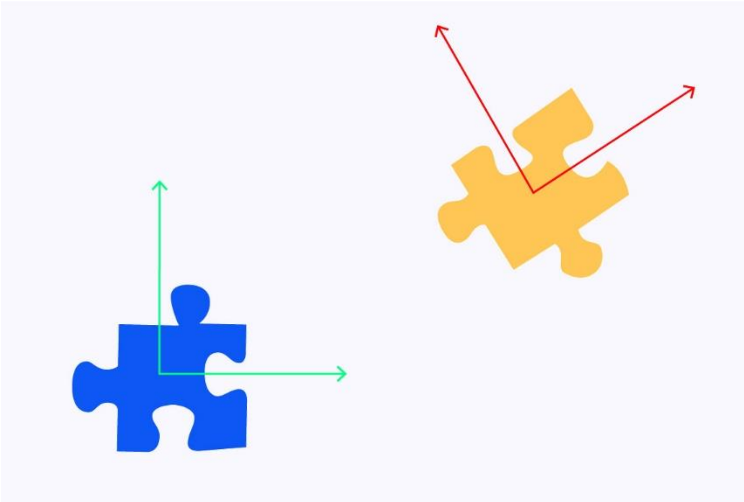


Figure 2: Local coordinate systems oft wo puzzle pieces or scans
(Liebler, i3mainz, CC BY SA 4.0 after Wujanz 2019b)

In the case of laser scans, six degrees of freedom usually must be determined, because translations (shifts) and rotations must be applied to the three cardinal axes X, Y and Z. Optionally, a scale factor can be additionally estimated. The graph below shows how the registration between scan A and scan B is calculated. The translation vector t (the relative displacement between both coordinate systems) and the rotation matrix $\boldsymbol{R}$ are available as registration parameters. With the latter, scan B can be transferred into the coordinate system of scan A.

$$\begin{bmatrix} x_A \\ y_A \\ z_A \end{bmatrix} = \boldsymbol{t} + \boldsymbol{R} \cdot \begin{bmatrix} x_B \\ y_B \\ z_B \end{bmatrix} \qquad (1)$$

The following figure shows a point cloud composed of 196 scans. You can see here how complex the correct composition of the individual laser scanner positions can be. Successful registration can already be indicated to the user in the field (see Figure 4). This requires a so-called "onboard registration" already in the laser scanner or the control software of the laser scanner on a tablet, for example.

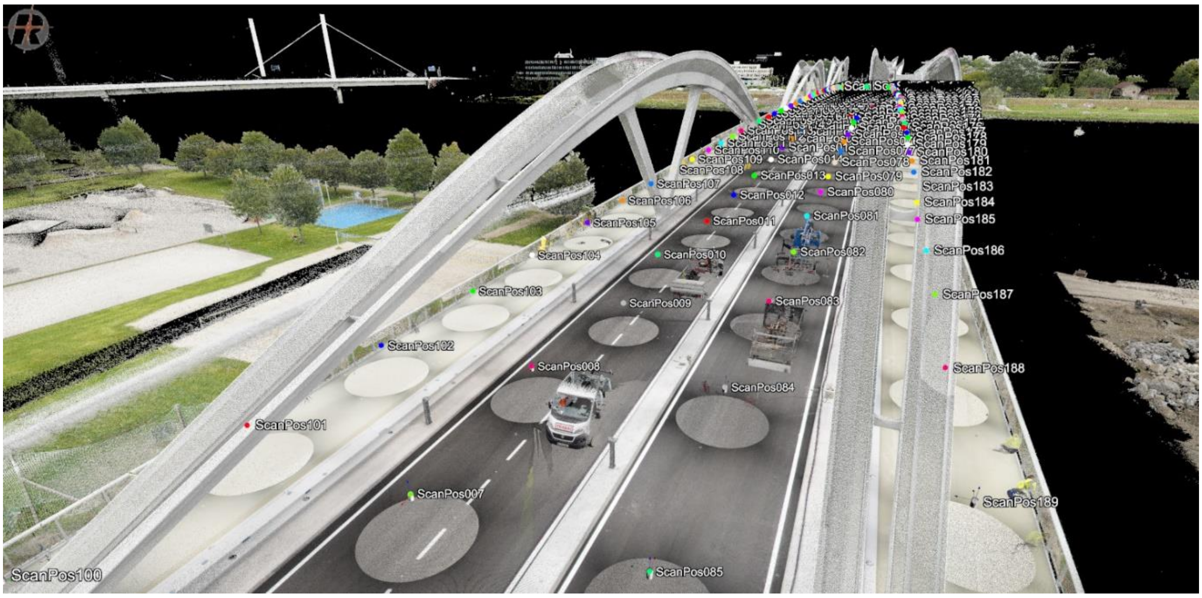


Figure 3: Colored point cloud from 196 individual laser scans

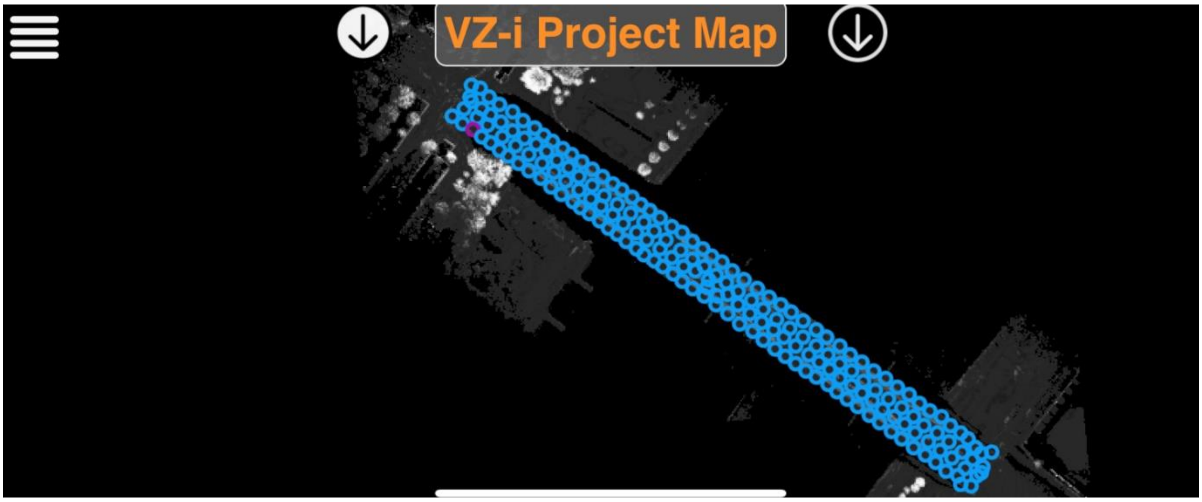


Figure 4: Display in the field: successfully registered point clouds of individual laser scanner positions

As we will see later, there are many ways to calculate or measure registration parameters. However, regardless of the strategy chosen, it is obvious that the accuracy of the registration has a direct impact on the final result. It may sound trivial, but the solution space becomes much larger and correspondingly more complex for problems with six degrees of freedom compared to those with three degrees of freedom, as the example of puzzle pieces has already shown. As a result, users of any registration software have to cope with inevitable misregistrations.

2.1 The Problem of Uncertainty Propagation

One thing that sensors and human beings have in common is that whatever you do, you always get it slightly wrong. In the case of sensors, this imperfection is referred to as noise or precision, uncertainty or accuracy, even though these terms have different meanings. In addition to knowing the accuracy of the laser scanner being used, it is equally important to know the major factors that affect the measurement result and be able to quantify them. Let us look at a simple example.

Imagine that a customer asks us to measure the distance between Berlin and Mainz with an accuracy of better than two millimeters. To save costs, we use a simple tape measure. Since the length of the tape measure is only one meter, we must determine the distance in small increments. This is achieved by repeatedly measuring a single meter and placing the tape measure at the virtual end of the previous length (Figure 5).

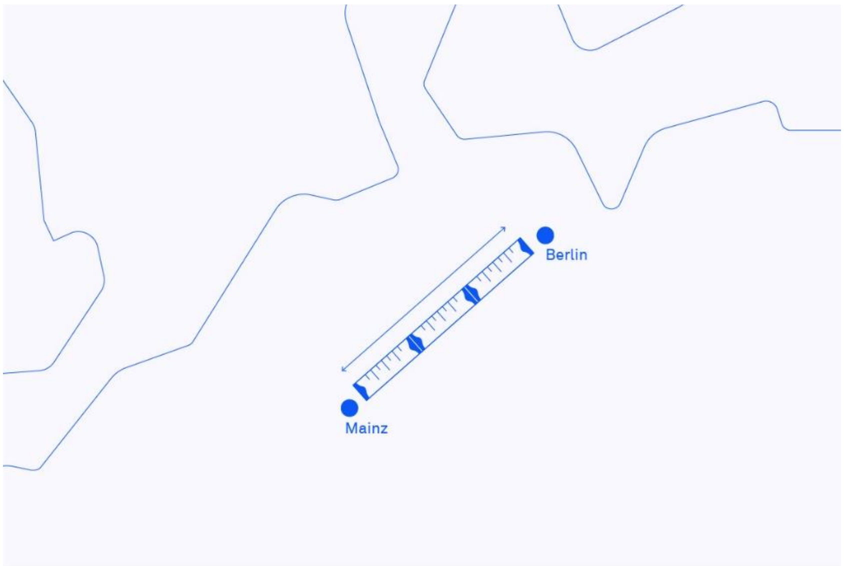


Figure 5: Determination of the distance between Berlin and Mainz by means of a tape measure (Liebler, i3mainz, CC BY SA 4.0 after Wujanz 2019b)

If the customer requires proof that we have met the accuracy required, we simply refer to a resolution and accuracy of one millimeter, i.e. that of our "measuring device." Here, however, we have neglected, among other influencing factors, the uncertainty of repeated application of the measuring tape.

A similar simplification is often used in TLS to convince potential customers. The influence of the registration is not considered here. It would be recommendable to use the concept of uncertainty propagation, which is well known in geodesy, to capture and quantify all influencing factors (Helmert 1872).

For this reason, geodesists always consider problems from two perspectives: a functional and a stochastic one. The statement "*The distance is 137 m …*" is, for you, only a part of the truth. The statement becomes complete only if you add "... and with an accuracy of 3 mm." The accuracy of a value depends mainly on two factors: the accuracy of the sensor and the when calculating the value.

Let us go back to the example of the puzzle and imagine that each piece represents a laser scan. Figure 6 illustrates the result of a registration from the functional perspective, i.e. through the puzzle itself in the center and the stochastic view, which is highlighted by semi-transparent puzzle pieces. It is obvious that directly adjacent pieces fit well together, so, it is reasonable to assume that the relative quality measures between two scans reflect equally precise values. What these numbers do not tell us is how uncertainty accumulates as more pieces are added to the puzzle.

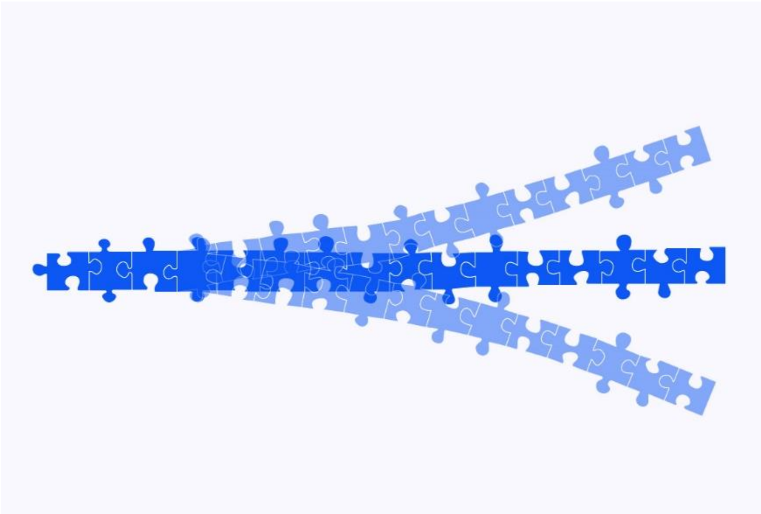


Figure 6: Effect of uncertainty propagation on the example of a puzzle game (Liebler, i3mainz, CC BY SA 4.0 after Wujanz 2019b)

The task of uncertainty propagation in the context of registering laser scans is, thus, to determine the resulting uncertainty due to the network configuration, taking into account various uncertainty factors. In essence, these quality measures indicate the geometric stability of the network, which is required to demonstrate, for example, that the laser scans registered are accurate enough to verify a scanned structure with respect to a specific construction tolerance or a customer's specified accuracy. Therefore, the task in performing registration is to design a network to meet the requirements specified.

2.2 Economic and Scientific Risks

Let us take a look at the economic impact of project-scale registration, shown in Figure 7. The figure shows four typical phases in laser scanning projects, starting with thorough planning and data acquisition. Once the data has been acquired, the primary data processing phase begins, such as file format conversion, filtering, and, of course, registration. In the second step, the actual results are produced, for example, by digitizing objects in the point cloud or performing deformation measurements between two different epochs. The vertical axis of the figure illustrates the possibility of influencing the result and the corresponding costs to bring about changes.

The unpleasant effect of registration is that (a) it can produce deviations that exceed the measurement accuracy of the laser scanner itself, and (b) causes systematic deviations that affect all other connected point clouds. Therefore, it is elementary to detect false registrations or tensions in the network as early as possible to avoid costly revisions.

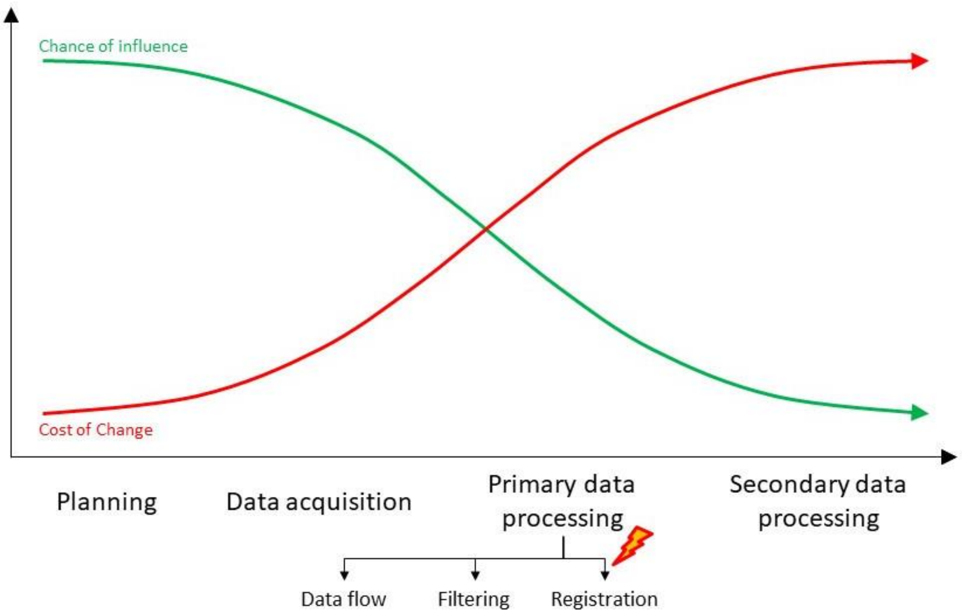


Figure 7: Influence of the registration in the process chain of the laser scanning project (Liebler, i3mainz, CC BY SA 4.0 after Wujanz 2019b)

3 Basics, Preparation, and Things to Know

Laser scans can generally be referenced by using redundantly acquired areas within point clouds (also referred to as (co-)registration), based on which registration parameters can be calculated, or by measuring their orientation and position with respect to a superior coordinate system by additional sensors in the laser scanner. In the following, various strategies for registration are listed and their basic modes of operation as well as individual advantages and disadvantages are explained.

3.1 How Much Overlap Do I Need?

It is obvious that an overlap between point clouds is needed to be able to register them. The crucial question is: How much? This question is controversially discussed in practice, and reliable statements cannot be made. To understand why the latter is the case, let us look at two examples where large-scale overlaps are present, as shown in Figure 8. The table represents one point cloud (which is considered as a reference coordinate system), while the piece of paper represents another point cloud.

In Chapter 2, we determined that three unknown rotation parameters and three translation parameters are needed to perform 3D registration. The scenario on the left side of Figure 8 contains enough geometric information to solve three degrees of freedom. Nevertheless, the piece of paper can be moved in two cardinal directions and rotated about the vertical axis, which is parallel to the surface normal of the table. The second example on the right shows a similar case but contains more "geometric contrast": the piece of paper has been folded at a 90° angle and is now "aligned" with the edge of the table. It becomes obvious that the higher degree of geometric information allows us to solve for five degrees of freedom. The remaining degree of freedom is the displacement along the edge.

These examples show that the overlapping region cannot be easily quantified. It is not possible to deduce from the quantification whether useful registration parameters can be determined. Geometric information for registration is needed that is approximately distributed in three mutually orthogonal directions.

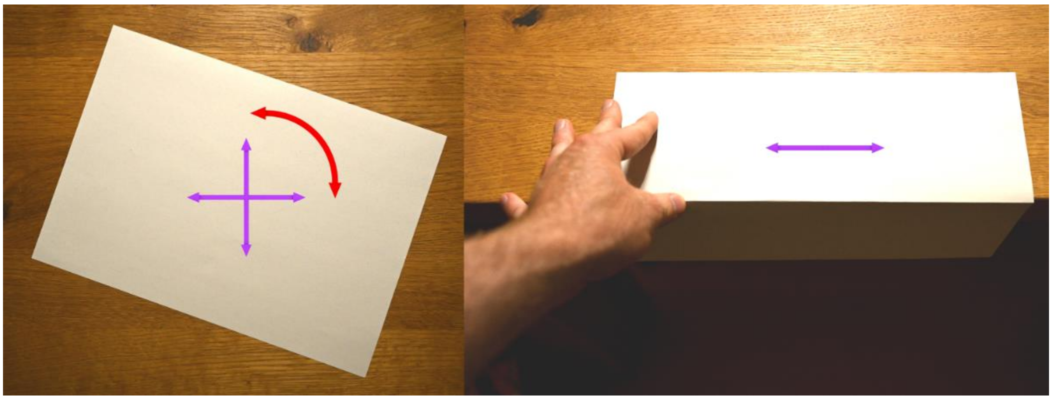


Figure 8: Overlap between two data sets, which makes it possible to determine three (left) and five (right) degrees of freedom, respectively (Wujanz 2019c)

The extent of the overlap required for a successful registration is usually only apparent to the experienced TLS user. The rather inexperienced TLS user is, therefore, recommended to choose rather small distances between the individual laser scanner positions at the beginning.

3.2 The Correspondence Problem

Imagine that we ask ten geodesists to scan the bust of Nefertiti. We will get ten different geometric descriptions, all of which are consistent in describing the same object, and yet they are not directly comparable.

Figure 9 illustrates this effect using three different scan lines taken from slightly different positions. It is obvious that the scans taken from different positions result in different point clouds. Imagine connecting all points from one data set to each other. We, thus, obtain three different triangulations of the scans. If we then transform these results into a common coordinate system, we get the result shown on the far right. It seems that the object has deformed while the scans were being acquired. This effect is called aliasing. It is unavoidable in laser scanning.

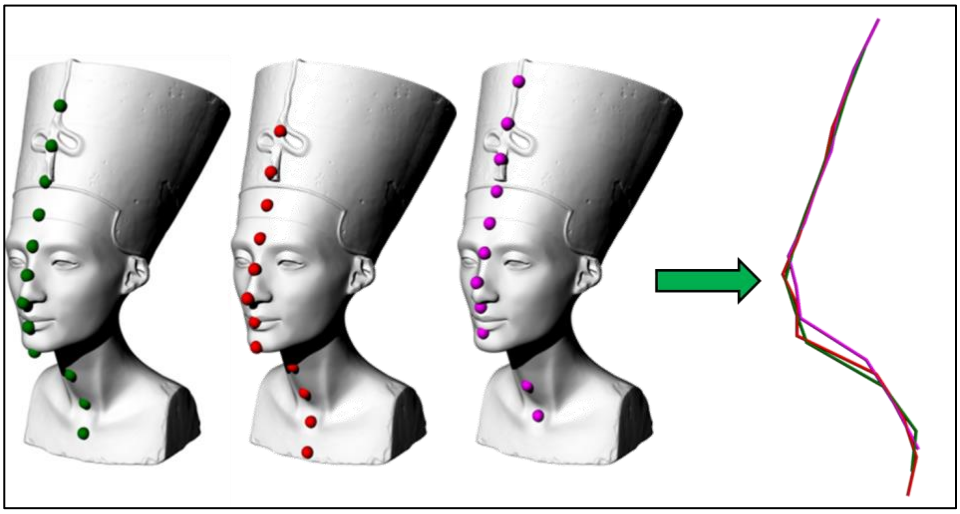


Figure 9: Emergence of pseudo-deformations due to aliasing
(Wujanz 2019)

The example above has shown that aliasing is an unsolvable problem, because you will usually never hit exactly the same points again with a laser scanner, even if you scan twice from the same position and with identical settings. Therefore, aliasing is rather bad news for the computation of registration parameters, since we must question the concept of point-to-point correspondences, which is widely used and established in geodesy. This also means that the local point resolution has a direct impact on the result. As we will see later, there are some concepts that are able to compensate for the effects of aliasing.

3.3 Point Cloud Preprocessing by Filtering

Even before the laser scans are registered, it is recommended to “clean up” the individual laser scans of the different positions (unless the registration already takes place in the laser scanner). Laser scans can be filtered (i.e. points deleted or masked) by the following parameters:

- **Amplitude (or reflectance) of a point**: The strength of the backscattered laser beam (laser pulse) is usually called "amplitude". It is basically dependent on the measuring distance. It can also be normalized to the distance and expressed in decibels (dB). In this case, one speaks of the reflectance. This is then largely independent of the distance. Particularly low values may indicate very small targets (particles in the air), distant targets, poorly reflecting targets or reflections. For poorly reflecting targets (such as the black steam locomotive in the following figure), the lower threshold value should not be set too high, otherwise too many points on the black surface will be erased. If the value of the reflectance exceeds the value of 0 dB, a retroreflective target is usually measured. But it can also be a total reflection at a glass pane. An example of a point cloud filtered by amplitude is shown in Figure 10.

Figure 10: Red dots indicate highly reflective targets (here: reflective stripes on the guards), green dots indicate weakly reflective targets.

- **Mixed signals** (also **"ghost points**" or **"mixed pixels"**): If an emitted laser beam encounters edges and other discontinuities and the laser is consequently reflected from different surfaces, this results in a distance measurement value that is an inaccurate averaging of the individual distances measured. Measurement points resulting from such mixed signals appear to float between real objects in the point cloud and are often referred to as "ghost points" or "mixed pixels." They can be filtered out for time-of-flight laser scanning by the pulse shape of the reflected laser pulse. If an emitted laser pulse hits two targets in a row (e.g. the spokes of a bicycle, see Figure 11), the point resulting from the reflected laser pulse (or double pulse) will usually come to rest between the targets. Its pulse shape, in this case, will be different from that of a single reflection. The pulse deviation can be classified with the deviation value, so that points between real targets can be eliminated during point cloud filtering with the help of this value. Examples of mixed signals detected in point clouds are shown in Figures 11 and 12.

Figure 11: Top: All points with a deviation value are highlighted. Bottom: These points have been deleted and shaded gray with the reflectance value.

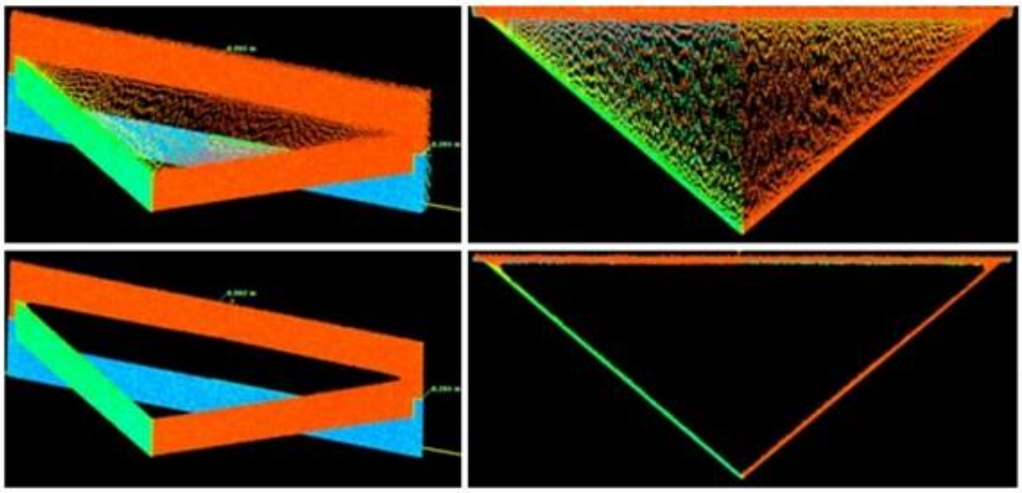


Figure 12: Top: "Mixed pixels" at an edge (left: oblique view, right: plan view). Bottom: The "mixed pixels" could be eliminated by filtering.

- A **range gate** can eliminate unwanted points in the immediate vicinity of the laser scanner, for example, if the laser scanner is mounted on a robot carriage and points on the robot carriage itself are unwanted (see Figure 13).

Figure 13: The laser scanner is mounted on a wheeled robot. It also measures parts of the robot itself. These points can be marked and removed with a distance filter (0 - 1.8 m), aka “range gate.”

- **Flying points** can be deleted with special algorithms.
- **Moving targets** (walking people, moving cars) are usually only included in a laser scan but not in a neighboring laser scan. Therefore, they can be automatically detected and eliminated using special methods (see Figure 14).

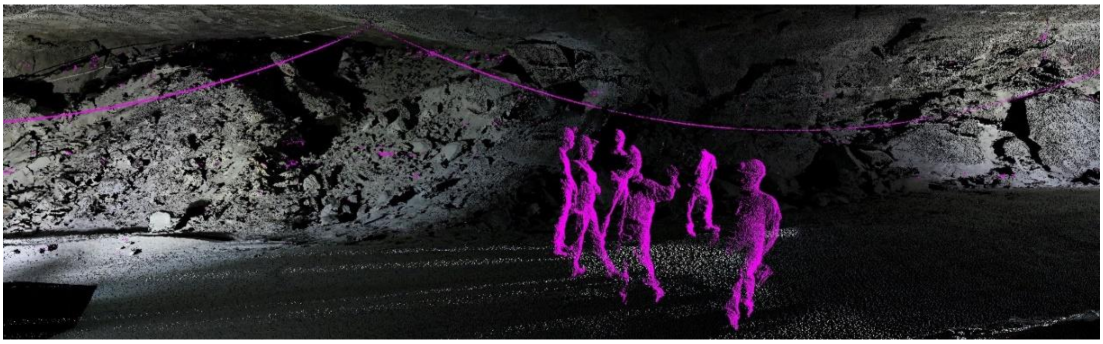


Figure 14: Targets moving in the point cloud (people and lines) were detected and highlighted (purple)

- **Reflections** (especially on window panes) can currently only be removed from the data sets manually.

4 Which Registration Procedure Do I Need?

As in all technical disciplines, no clear answer can be given to the question posed in the heading. Just as there is no single laser scanner on the market for all applications, there is also no single registration method (or solution consisting of several algorithms) that works perfectly for all possible tasks. Thus, the answer to the question must be "All!" because in practice, mostly different solutions are conceivable, even within a single project.

The registration procedure must be selected individually depending on the measuring environment and the measuring object itself. For this purpose, it is absolutely necessary to know at least roughly how the registration methods work. Individual registration methods are described and their advantages and disadvantages are discussed in chapter 5. It is important to understand that a reliable registration of measurement data does not end with the calculation of pairwise registration parameters. This calculation is only an intermediate result of a superior process.

As has already been mentioned in chapter 2, all registration procedures can fail. Therefore, one must refrain from using a qualitative evaluation based on relative quality measures which are based on single registrations. Instead, it must be verified that the results obtained are free from errors, contradictions and tensions. These results are based on redundant information – just as it has been common practice in surveying to process measurement data for over 200 years (Legendre 1805, Gauss 1809).

Transferred to the determination of registration parameters, this means selecting laser scanner positions in such a way that the measurement object is scanned redundantly, and, thus, networking is achieved between a wide variety of laser scanner positions. This network can significantly increase the reliability of the registration parameters determined. This second part of the process is called network or block adjustment (Jäger et al. 2005, p. 237 ff.). All observations, for example, tacheometric control points, inclinometer observations and registrations, are included in this process. The result of the block adjustment, thus, helps to identify and eliminate erroneous observations in the network, which would otherwise cause costly revisions in the production or post-processing phase, see section 2.2. As soon as the block adjustment no longer shows any significant discrepancies, the registration process can be regarded as completed.

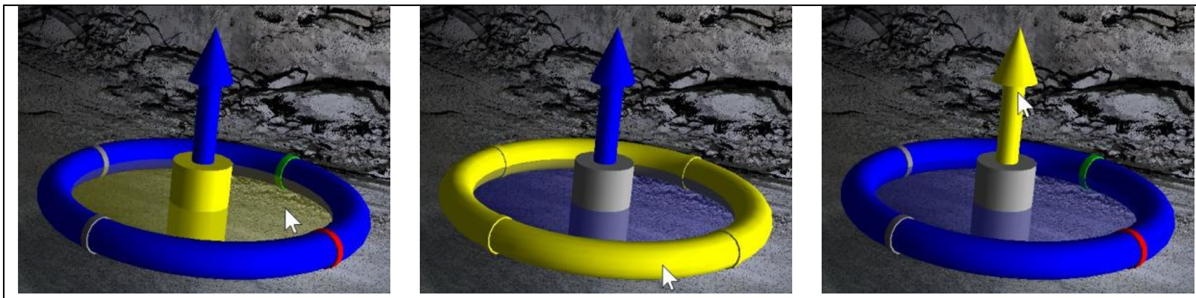
5 Registration Methods

In this chapter, different methods for registration are presented, which are used either standalone or in combination. As a rule, registration is subject to a cascading process in which the relative position and orientation of point clouds is refined step-by-step. Which algorithms are used or which process sequence is run through depends, among other things, on the object itself and/or the existing conditions on-site. Prealignments of point clouds, for example, can be determined with the help of GNSS in open air but not in indoor spaces where, among other things, inertial measurement units are used. Registration can generally be divided into two main approaches. One comprises registration algorithms, where the registration parameters are determined based on redundantly acquired areas within two point clouds. The registration method referred to as direct (geo) referencing (see Section 7.5) differs fundamentally from this, because the registration parameters are determined directly by the usage of sensors.

5.1 Manual Prealignment

The simplest method for prealigning point clouds is manual prealignment. It is used when there is no automatic algorithm to align the laser scans. This can be either at the very beginning of the registration process, or to correct a misaligned registration. Since this manual intervention is very time-consuming, especially when several hundred scan positions are involved, manual prealignment should be the exception and not the rule. It is necessary to shift or rotate the last laser scan so close to the previous one that the following iterative closest point (ICP) algorithm (cf. Section 5.4) can push the point clouds together "to the millimeter." Three tools are usually available for this purpose: (i) shifting in the x/y plane, (ii) rotating in the x/y plane and (iii) lifting in the z-direction. The symbols shown in Figure 15 show the currently active tool in yellow (taken from the RiSCAN PRO software).

It is assumed that the laser scan positions are leveled sufficiently accurately, i.e. that they no longer have to be tilted in the x-y plane. Inclination sensors are normally used for the measurement of the laser scan inclination. If this degree of freedom is also released for the user, there is a risk that entire projects will be tilted.



Moving a scan position | Rotating a scan position | Lifting a scan position

Figure 15: Examples of tools for the manual prealignment of laser scanner positions

5.2 Target-based Registration

Artificial targets are used to determine the transformation parameters between the individual laser scans in target-based registration. This makes it possible to transform the 3D point clouds present in the laser scanner coordinate system into a uniform superordinate system.

The artificial targets must be placed within the scene to be measured before the scanning process. In order to be able to determine the transformation parameters between two laser scanner positions, at least three identical targets must be measured from both positions. The user has a decisive influence on the quality and reliability of the transformation parameters to be calculated by the positioning of the targets in the laser scanning environment. Various factors must be taken into account, such as the distances to the targets, the angle of incidence of the laser beam (relevant for some targets) and, the visibility.

The decisive factor, however, is the arrangement of the targets relative to each other (network geometry). The planning of the target network is not trivial. The position of the targets must be chosen in such a way that they have a good 3D distribution (do not lie on a straight line) and are visible from different laser scanner positions. Depending on the object to be measured, the number and position of the laser scanner positions must be chosen. In order to be able to guarantee a time-optimized complete object scanning, a good position planning is the best basis. Only this makes it possible to obtain optimal and reliable solutions with the accuracy required.

Planar or spherical targets are normally used. The vast majority of algorithms in commercial implementations use methods based on image correlations for the determination of the centers of planar targets. If planar targets are mounted on curved surfaces, such as pipes, or scanned from very oblique angles of incidence, this can result in incorrectly detected target centers. The user must ensure that only perfect targets are used. Figure 16 shows examples of insufficient targets that must not be used for registration in this way.

a) b) c) d)

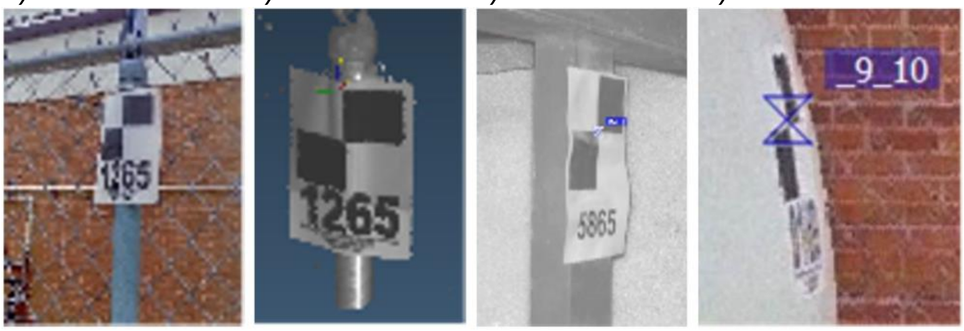


Figure 16: Examples of insufficient targets:
(a-c) planarity of targets not given, (d) angle of incidence too shallow

A major advantage of artificial targets is that they can be measured tacheometrically. If the coordinates of the artificial targets used are known in a superordinate coordinate system, individual scans or scans that have already been registered can be transformed into this coordinate system.

If the registration of different laser scan positions is to be based solely on artificial targets, the application of the targets can take a long time, because a minimum number of identical targets must be visible between the laser scanner positions to be registered. This fact represents an almost unsolvable task for some measurement objects. From a purely economic point of view, it is therefore advisable to use targets for the registration of extensive laser scanning projects only as a supporting registration option.

5.3 Prealignment by Additional Sensors

The automatic finding of start values for the registration is not trivial. However, these are of special importance for the registration because all registration procedures can end in local minima if unsuitable start values were chosen. What does it mean? You get a set of registration parameters that misalign scans that are already misaligned, and that is not productive. Probably the biggest revolution in TLS has been to equip laser scanners with additional sensors that allow measuring differences in position and orientation between scans to be inferred from measurement data. Figure 17 shows two viewpoints with two different local coordinate systems, which leads, consequently, to differences in orientation and position.

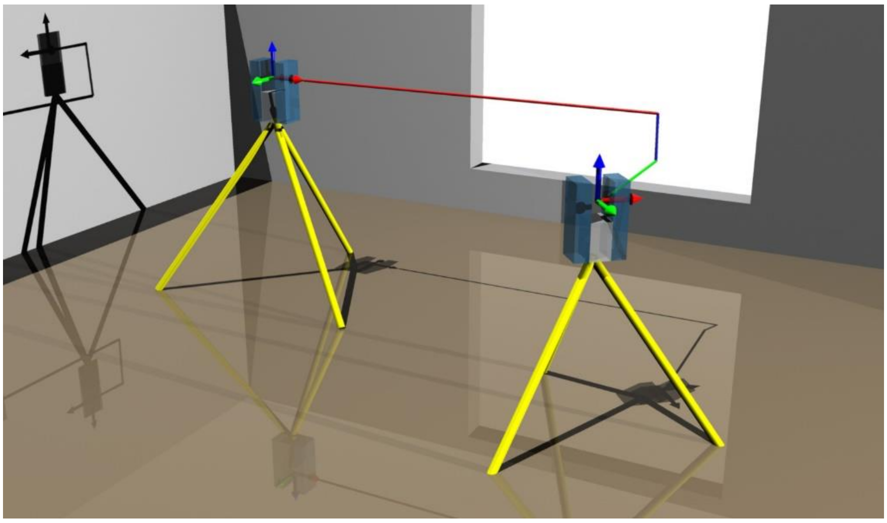


Figure 17: Two stations with different orientations and positions (Wujanz 2020a)

5.3.1 Strategies for Prealignment Using Additional Sensors

Early developments often used GNSS techniques (Reshetyuk 2010) to determine viewpoint positions in a superordinate coordinate system or, additionally, orientation differences (Paffenholz 2012). Since satellite navigation relies on direct line-of-sight to satellites, these strategies are useful for outdoor tasks but not very useful for indoor data collection. Meanwhile, laser scanning uses additional sensors, such as accelerometers, gyroscopes, barometers, compasses and cameras, to derive a prealignment both outdoors and indoors.

Direct (geo) referencing is usually much less accurate than the results obtained by registration. The reason for this is that sensors have limitations in terms of accuracy. However, the sensors used are good enough to provide sufficient prealignment and, thus, approximations for subsequent ICP registration, in turn, avoiding local minima and reducing the number of iterations in ICP algorithms. In addition, prealignment can be used to achieve an automated registration process (see Section 5.3.2).

Another advantage of using additional sensors to compute prealignments is related to combinatorics/permutations. Consider a standard network with 1000 scans. Checking all possible combinations results in 499’500 combinations, which would be computationally very challenging. Therefore, the question is how to reduce the solution space. The first possibility would be to define a search radius in which another station is considered as a direct neighbor. However, two laser scans could be one meter apart and still have no overlap because there is a wall in between the two positions. Therefore, one could sort the roughly registered laser scans into a 0 tree structure (Samet 2006) to clarify whether there are overlapping areas between the laser scans that can be used for registration

Table 1: Prealignment sensors used in terrestrial laser scanning

Sensor	Measured value, remark	Accuracy
GNSS	Absolute position (outdoor only)	DGNSS (L2 RTK): a few centimeters GNSS (L1): a few meters
Acceleration sensors	Gravitational field, rotations about the x- and y-axis	In robust mode approx. 0.01°
3-axis magnetic field compass	Earth magnetic field, rotation about the z-axis	Several degrees, depending on the metal in the environment
Inertial measurement unit (IMU)	Relative pose determination in relation to the previous laser scanner position	Typical: 30 cm with 10 – 20 s continuous movement when changing position (strong drift thereafter)
Barometer	Helpful if the GNSS altitude was not measured accurately enough.	Approx. 1 meter

5.3.2 Automatic Registration by Prealignment Using SLAM

Newer strategies in automatic prealignment rely on visual SLAM (simultaneous localization and mapping) algorithms. During the movement of the laser scanner from one position to the next, images from the cameras installed in the laser scanner are continuously evaluated. At the start, optically distinctive features are automatically detected in the camera images at the starting point, so that the starting position can be determined by means of their 3D positions in the previously captured point cloud by resection. As the laser scanner is transported to the next position, these features are tracked in the images for continuous position determination. In addition, other features are continuously detected and tracked as the scanner moves, and, finally, their 3D position is determined by intersection to replace 3D features that leave the cameras' fields of view with new ones (see Figure 18). This ensures that there are always enough 3D positions available for position determination by resection for the entire motion sequence until the laser scanner is set up on the next position. The position determination based on the camera images can be supported in a Kalman filtering by the data of an IMU. Upon arrival at the next position, all measurement data are finally subjected to a global bundle block adjustment (Leica Geosystems 2020).

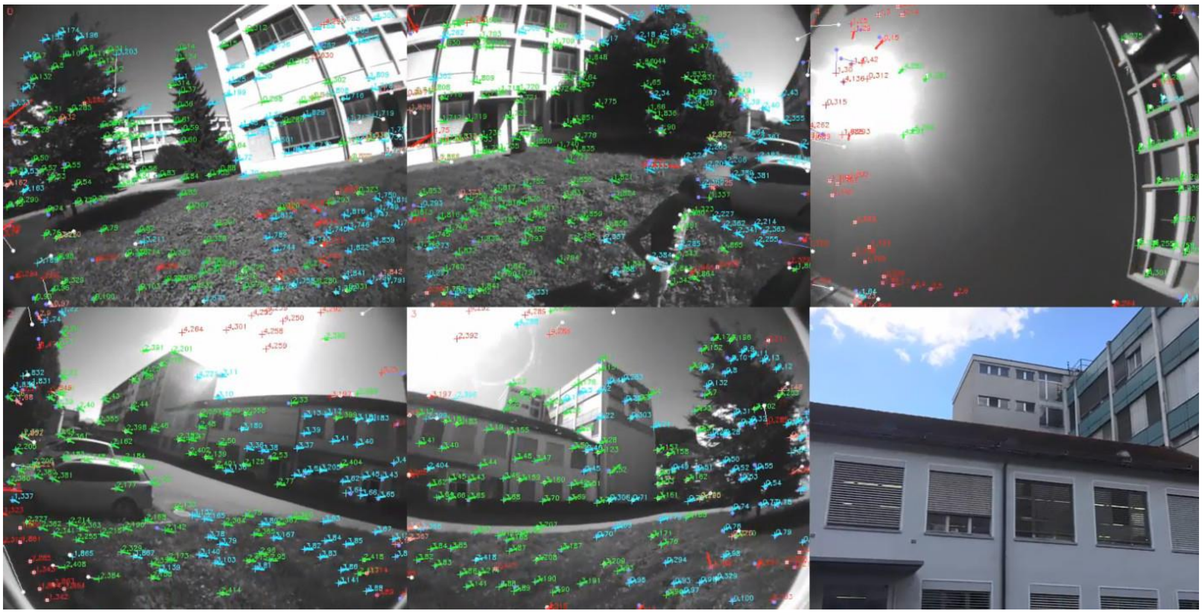


Figure 18: Features detected and tracked in the visual SLAM camera images (visualization of the algorithm running in the background: green dots stand for features tracked by means of the camera considered, blue dots for features tracked by means of a neighboring camera. Red dots stand for features detected as outliers)

In this way, registration parameters to laser scans of previous positions for each point cloud on a new laser scanner position can be determined automatically, and are sufficiently accurate to register the entire point cloud association automatically in a next step, for example, by means of ICP.

Due to the support of the IMU and in combination with an automatic feature-based registration algorithm, the registration procedure using visual -SLAM can also be used reliably in dark measurement environments.

5.4 The ICP Algorithm («Cloud-to-cloud registration»)

The most versatile registration method is the ICP algorithm, which is also called cloud-to-cloud registration in practice. The basis of the ICP algorithm is redundantly acquired regions of two laser scans, based on which the registration parameters are calculated. The algorithm aims at minimizing the distances of overlapping parts of the laser scans by varying the position and rotation of the laser scan to be matched in an iterative process. This process ends when a convergence criterion is met. The ICP method thus minimizes the point spacing in overlapping areas of laser scans.

A major advantage of this strategy over target-based registration is the actual use of redundant information in the overlapping regions of two or more laser scans. The ICP-based algorithms rely on sufficient prealignment of two data sets, otherwise there is a risk that the optimization algorithm will converge to a local minimum, leading to erroneous results.

The general concept of this ICP algorithm is shown in Figure 19, where the initial situation is shown in the red boxes. There are three general ways to achieve the prealignment: (i) by manually determining a few correspondences, (ii) by measuring the individual position and orientation of two laser scans by using auxiliary sensor technology (see Section 5.3.2), which is now commonly found in modern laser scanners, and (iii) by using prealignment algorithms.

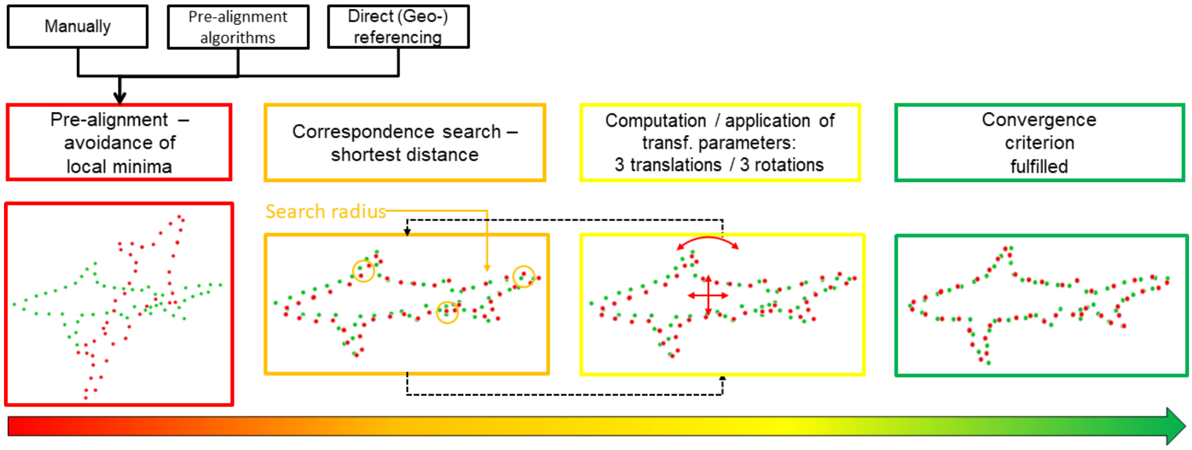


Figure 19: Procedure of a registration by means of an ICP algorithm (after Wujanz 2019c).

The next step (orange in Figure 19) is the correspondence search. Depending on the implementation, correspondences are determined either by the shortest distances between one point to another (Besl & McKay 1992) or from one point to a plane (Chen & Medioni 1992). Based on this information, registration parameters are calculated and applied to one of the data sets (yellow in Figure 19). The black dashed arrows between the orange and yellow boxes indicate that these steps are iteratively repeated until a convergence criterion is met and the final solution is found. One consequence of the iterations is that different correspondences are established during the algorithm.

A common problem in ICP-based algorithms is quality assurance, which is illustrated in Figure 20. The input is two completely different data sets acquired with a commercial solution. The algorithm settings can be found in the lower left of Figure 20. The sample size indicates for how many points the ICP should try to find correspondences. This value is usually limited to a few thousand points to keep the runtime and memory consumption low. The second value determines the largest distance between two points from two data sets that can form a correspondence. It is obvious that the resulting quality measures of the ICP are always smaller than this value. The right side shows the result generated, which is obviously nonsensical, although the numerical quality measure, which is the mean residual of the corresponding points, suggests a very accurate result. This example illustrates a property of the ICP algorithm: it always finds a solution, but not necessarily the correct one. Therefore, in practice, the result is typically checked by a visual inspection. However, simply looking at data is quite subjective and can only be done on a random basis.

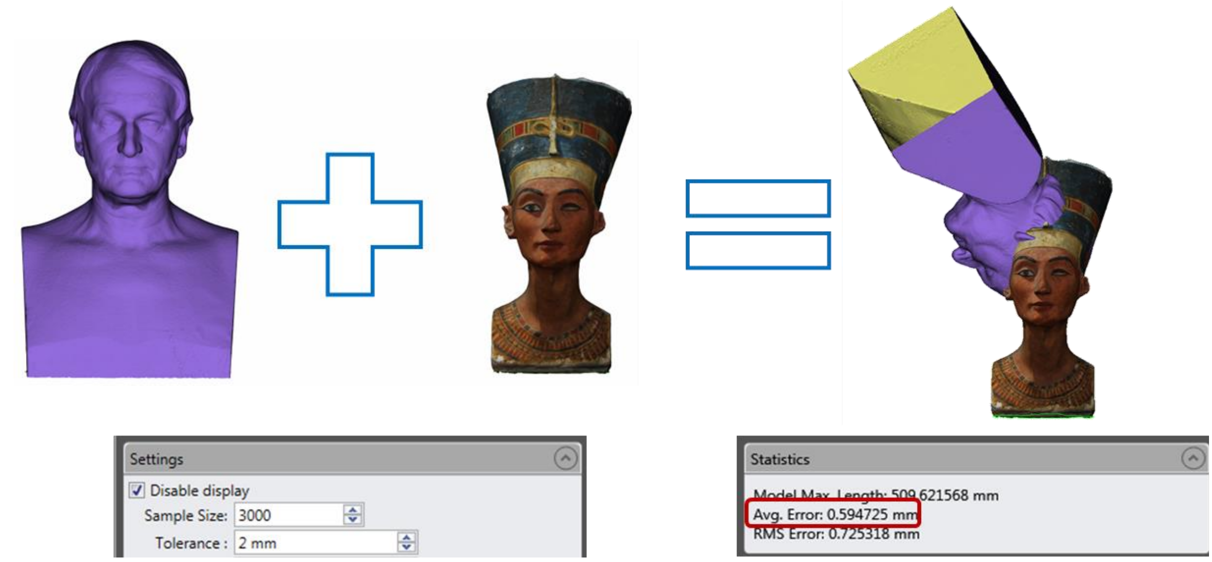


Figure 20: The problem of numerical quality assurance with ICP (Wujanz 2019c)

5.5 Voxel-based Automatic Registration Procedure

In practice, it has been shown that with the increasing size of the measurement area, the positioning and installation of targets is time-consuming and, therefore, uneconomical. In order to efficiently survey large areas with a laser scanner, targets should, therefore, be avoided as far as possible (except for a few that are used for accuracy verification). This requires an automatic registration procedure, since many laser scans cannot possibly be registered manually. Before the precise ICP procedure (see Section 5.4) can be applied, the laser scan to be registered must be automatically aligned a priori with sufficient accuracy to the laser scans already registered. It is important that this is done in a process that is as robust as possible, i.e. independent of ambient light, GNSS reception or target characteristics. The method presented here only requires a sufficient overlap of the individual laser scans.

The first step in the so-called voxel-based automatic registration method is to reduce the data volume of the laser scans to the necessary part. A laser scan with typically more than 20 million measurement points is reduced to a voxel data set with a few hundred thousand voxels. Here, a voxel (cube) represents a large number of measurement points of the laser scan acquired. The voxel sizes given in the following table have proven to be useful in practice. They are determined once in a laser scan project and are roughly dependent on the laser scan range, i.e. on the environmental conditions. This voxel data set can be regarded as a "spatial signal" and represents the basis for the transition by means of the Fourier transformationfrom the spatial range into the so-called spectral range. The decisive property of the Fourier transform for this application is that a shift and rotation of a data set in the spectral domain is represented in such a way that the rotation only shows up in the Fourier transform of the transformed data set (Ullrich 2017).

Table 2: Voxel sizes for automatic registration of laser scan positions

Scene	Voxel size
Small interior scene	5 cm
Large interior scene	10 cm
Urban outdoor scene	25 cm
Outer urban area	50 cm

With sufficiently large overlaps, this method allows a robust determination of the six degrees of freedom of the newly determined laser scan position in relation to the data previously registered. In this first step, a registration accuracy of less than one voxel size can be achieved, i.e. a few centimeters. The "millimeter accuracy" of the registration is achieved by a modified ICP algorithm. When all scans of a project have been registered correctly, a final block adjustment can minimize the residual deviations.

The steps of the voxel-based automatic registration are visualized in Figure 21.

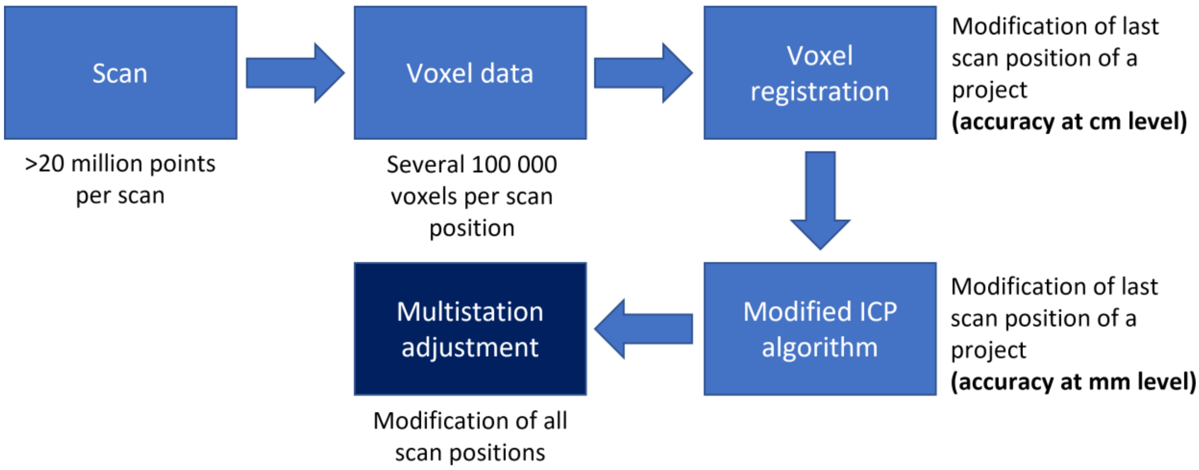


Figure 21: Steps of the voxel-based automatic registration process

Since the process described is automated, it can also be implemented in the laser scanner itself (except for block adjustment). The resulting voxel data set can already be displayed during scanning and thus serves as an orientation assistance for the operator, as the following figure shows.

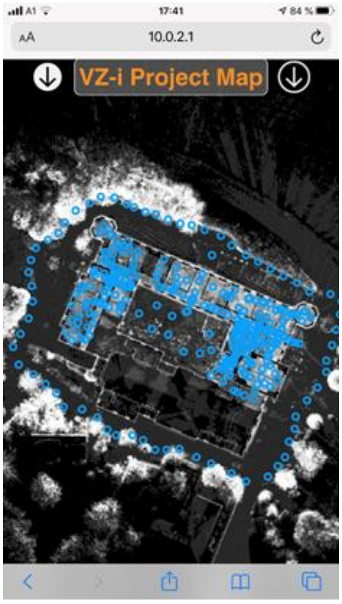


Figure 22: The voxel-based automatic registration process running on the laser scanner allows the display of laser scan data and positions already during the scanning process.

A distance between successive laser scanner positions of about ten steps has proven to be optimal in urban outdoor areas. This results in a dense, overlapping point cloud describing almost the entire surface. The scan gaps are reduced to a minimum and the so-called “street inventory” can be completely scanned. The positions’ distances are sometimes much smaller inside buildings. Registerable scan chains with distances between the individual laser scanner positions of up to 40 meters have proven to be reliable in open spaces and on highways.

5.6 Registration with Geometric Primitives

It is time to move on: instead of using artificial targets for registration, some more natural information will be used. Natural, in this context, means that geometric primitives – (such as spheres, cylinders (Moritani et al. 2019) and planes (e.g., Previtali et al. 2014, Wujanz et al. 2018), and others) – that may be inherently given in a scene are used to compute the registration parameters. The first step of this procedure is a segmentation process in which individual points are assigned to a primitive. Figure 23 shows an industrial scene as an intensity image after segmentation. In this case, planes were detected that are colored depending on the direction of their surface normals.

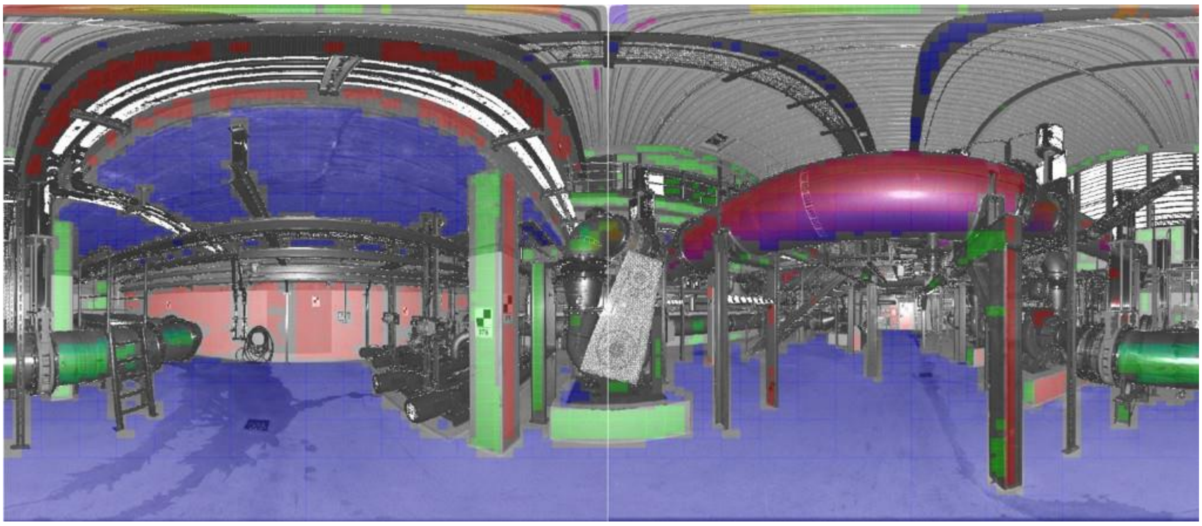


Figure 23: Detected planes, colored depending on the direction of their surface normals (Wujanz 2020a)

All segmented points are then used to estimate parameters depending on the respective geometry object (primitive). Correspondences between the geometric objects detected must then be established to compute registration pairs between laser scans. In contrast to ICP (see Section 5.4), these procedures are not iterative and, thus, much less dependent on the settings selected. Additionally, since each adjustment provides stochastic measures, these values can be used to weight individual primitives during registration, so that precise parts of a scene have a higher impact on the result than less precise parts. Using geometric primitives for registration has several advantages, the first being the reduction in complexity. Instead of millions of points, only hundreds or thousands of primitives are processed, although the original information is taken into account. The second advantage is a significant increase in accuracy, because adjusted parameters are more accurate and reliable than single points, for example, used in the ICP algorithm. A third aspect in favor of these approaches is their invariance to differences in point sampling (see aliasing in Section 3.2). However, where there is light, there is also shadow: if the scene does not contain a sufficient number of well-distributed corresponding primitives, this strategy will fail. Geometric primitives are typically found in man-made structures, such as buildings, factories or bridges.

6 Quality Assurance in Laser Scanning

A final visual check of processed measurement data is not to be questioned in surveying, regardless of the measurement equipment selected. What must be critically questioned, however, is the common practice in laser scanning of performing a visual plausibility check as the only quality assurance measure. Although gross registration deviations can usually be detected visually, the sheer quantity of points and the limited perspective when viewing 3D data do not allow for the detection of small subtle deviations, which become a problem, at the latest, when they manifest themselves in visible discrepancies. This approach can be explained by the mistrust of many users toward numerical quality measures (see e.g. Figure 20), which, according to the widespread opinion, are not meaningful. Therefore, this chapter, firstly, discusses different metrics for numerical quality assurance and shows their advantages and disadvantages.

6.1 The Concept of Redundancy

The prerequisite for reliable quality assurance in surveying, as in many other technical disciplines, is redundancy. Let us first look at this with an example.

The wheels of a normal car are usually fastened to the hub by five wheel nuts, while each wheel on racing cars is secured by exactly one central locking device. If you lose one of the central locks, you also lose a wheel, including all the unpleasant consequences.

When processing measurements, redundancy or overdetermination has been the key to (a) controlling and verifying measurements and (b) improving the quality of a network – regardless of which geodetic sensor was used to collect the data. An urban myth often mentioned in the laser scanning community is that you must control your registrations with an instrument of higher accuracy. We should, therefore, think through this logic.

One controls terrestrial laser scans, for example, by measurements from a total station. But how does one know that these measurements are correct? According to the logic above, to control tacheometric observations, one would have to use a laser tracker with a higher accuracy than that of the total station. But how does one know that the laser tracker measurements are correct …?

While the general idea is understandable – you increase redundancy within a network by adding observations – there are always economic limitations. You cannot measure every single station in the network for quality assurance, because that would simply be unprofitable. If one wants to stabilize the network, for example, by adding tacheometric control points, in order to satisfy, for example, the accuracy required, then this is a completely different problem, which we will discuss at a later time. Firstly, our goal is to create a network that is free of discrepancies between adjacent laser scans. Ways to increase the redundancy of a laser scan network by adding observations are to:

1. Introduce GNSS, tacheometric, and/or leveling measurements

2. Add more pairwise registrations

3. Incorporate data from inclinometers.

Figure 24 shows a scanning project based on a publicly available dataset (see link to Leica Geosystems (2018), click on "Indoor multi-setup data"), with circles marking scanning locations and arrows marking registrations. The network on the left does not contain redundant registrations, therefore, it is not possible to check whether the network contains erroneous registrations. The same dataset was then processed in a redundant and, thus, self-checking configuration, where each scan is connected by at least two registrations.

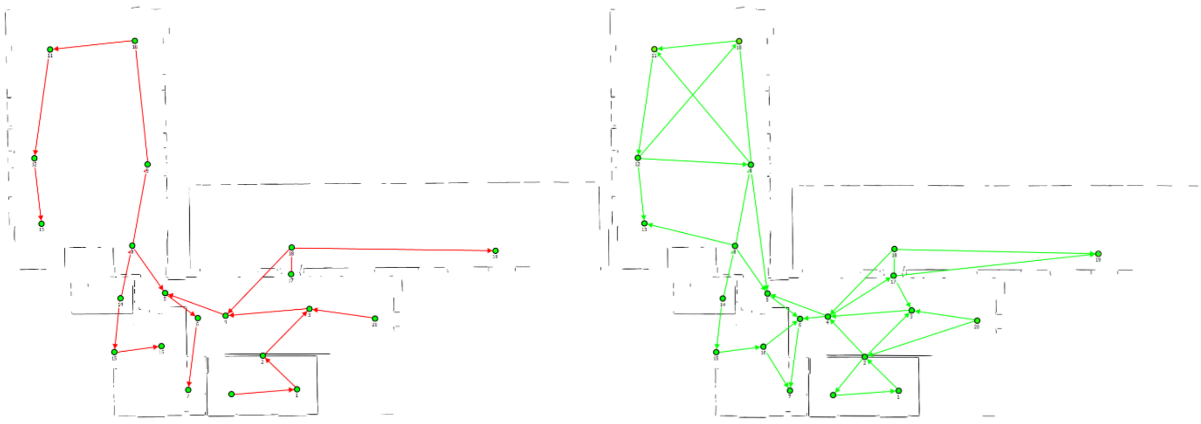


Figure 24: Uncontrolled network configuration (left) and self-controlling network configuration (right) (Leica Geosystems 2018)

6.2 Calculation of Numerical Quality Measures

Overlooking registration errors can be very painful financially and also damaging to a company's reputation. It is not advisable to base registration quality assurance only on visual inspection, as this leads to a user-related and, thus, subjective quality assessment. Instead, it is advisable to detect deviations in registration by reliable and meaningful quality measures, regardless of the registration method chosen. However, deriving "meaningful quality measures" can be challenging in the laser scanning context.

One scientific field that has developed many meaningful quality measures over the centuries is geodesy or surveying. Therefore, it is very surprising that the vast majority of the entire laser scanning industry associates "quality" with only one measure, namely, residuals. The main problem is that residuals can be calculated in different ways. Therefore, you need to understand what kind of residuals you are looking at, what they say and, most importantly, what they do not say.

Amounts of residuals are, in geodetic terms, datum independent. This means that these quality measures always remain the same, even if the point clouds are arbitrarily moved or rotated. Note that (a) residuals may refer to pairwise registrations, where the residuals between two laser scans are minimized (Besl & McKay 1992), or (b) residuals may originate from a block adjustment (Pulli 1999), where the inevitable discrepancies between all redundant pairwise registrations are minimized. The biggest problem, however, is that three strategies for computing residuals between laser scans have become prevalent in laser scan registration, which are discussed below, namely:

1. Residuals between discrete points (target centers), cf. 6.2.1
2. Residuals between laser scans themselves, cf. 6.2.2
3. Residuals between redundant registration parameters (block adjustment), cf. 6.2.3

6.2.1 Residuals from Derived Points or Targets

Artificial targets are widely used in practice because their quality measures are meaningful and easy to interpret. Since the general workflow and metric interpretation are generally comparable to geodetic observations, these numbers feel quite familiar to many people, especially surveyors. Basically, targets are used for the pairwise registration of laser scans and/or for transferring them to a superordinate system. Firstly, the local (pairwise) case is considered.

Figure 25 illustrates a scenario with three stations registered with three spheres. The colors of the spheres show from which point of view they were registered. Since the trio of spheres was registered from three stations, there are nine spheres in Figure 25. The quality measures after a target-based registration are residuals (also called residual gaps). These describe the remaining tensions between the individual target centers after they have been transferred to a common coordinate system.

To transfer the laser scans acquired into a superordinate coordinate system, superordinate coordinates must be determined for the individual targets with the aid of geodetic measurements. These additionally increase the redundancy of a network and are of great value as an independent control instance. However, their introduction is always associated with additional effort, which has a direct impact on the economic efficiency of a project. Consequently, the question arises in practice regarding how many control points are required at what accuracy to achieve a quality objective.

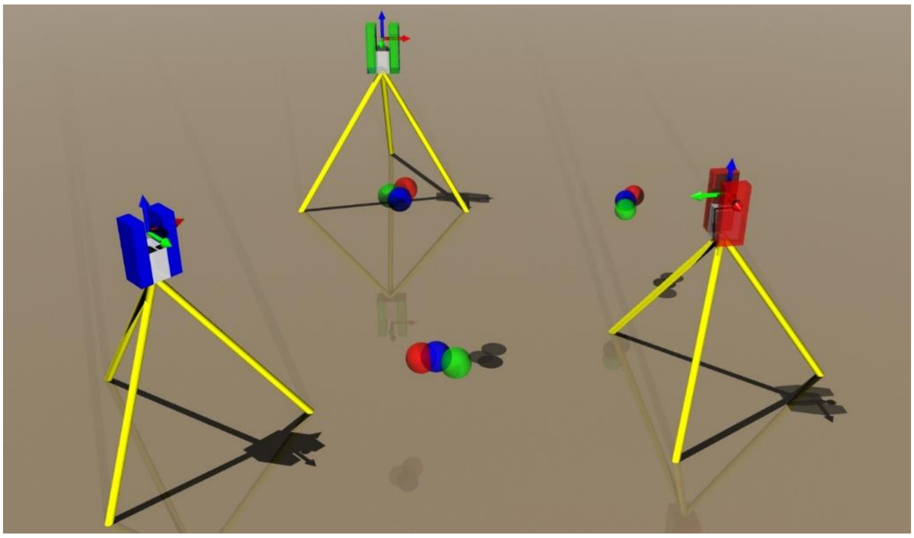


Figure 25: Registration of three laser scans by local targets

6.2.2 Residuals Between Point Clouds

Residuals between overlapping point clouds can be calculated in two ways. A common feature of both strategies is that not all points lying in the overlapping area are used for the calculation of the quality measures but only a selection. As a rule, this selection comprises a few thousand points in order to reduce the runtime required and the memory load to an appropriate level. The geometric distribution of the points selected is usually hidden from the user, with a regular grid representing the optimal solution (Wujanz 2012).

An example is used below in Figure 26 to illustrate the two strategies. Here, a section through two registered point clouds is shown, highlighted by green and orange spheres. The digitized area is represented by a gray line. How the laser scans were registered is irrelevant in this context.

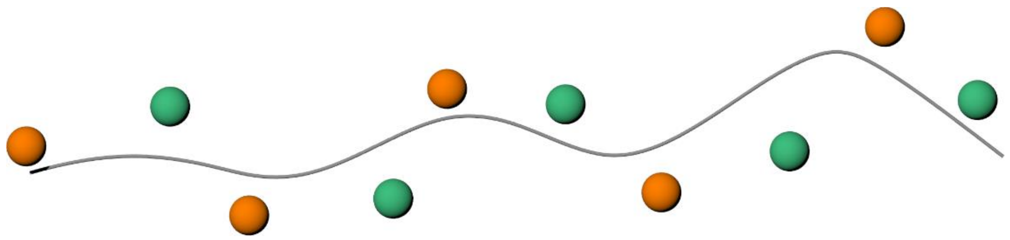


Figure 26: Section through two registered point clouds (Wujanz 2021a)

The first strategy is based on the formation of point-to-point correspondences. For each point selected from the first point cloud, the nearest point from the second point cloud is determined. In this example, four green spheres were selected to calculate the quality measures for this registration. Regarding the example shown in Figure 27, the selection was made from left to right, starting from the first green sphere. It is obvious that a reverse order would result in different correspondences and, therefore, different quality measures.

The particular correspondences are highlighted by yellow links in the following figure. Their length indicates the size of each residual. As a last step, a single numerical value is calculated, for example, the mean of all residuals. Concerning the present case, this value is an average of 7.8 mm (residuals from left to right: 7.8, 7.0, 7.4 and 9.0 mm).

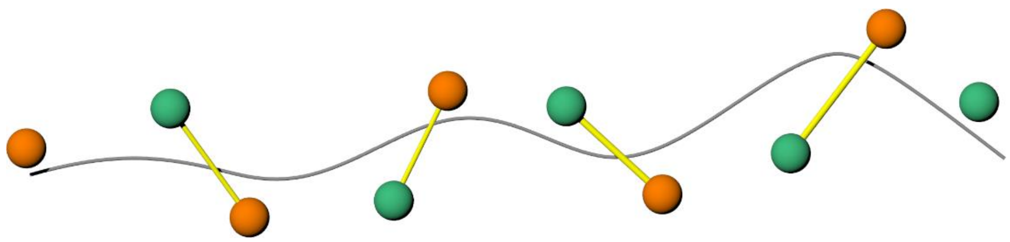


Figure 27: Formation of point-to-point correspondences (Wujanz 2021a)

It is obvious that the effect of the local point distribution has a large impact on the quality measures calculated previously. Therefore, the identical scenario shown in Figure 26 and 27 is now run again by calculating point-to-triangle correspondences, as shown in Figure 28. In the first step, the orange data set was triangulated, as illustrated by the light gray colored straight segments. Triangulation is usually performed only locally, around selected points. Subsequently, the green points are projected onto the corresponding triangles, if possible. The distance between a green point and the projected perpendicular base point represents the resulting residual. In this example, the "quality" of the registration is 3.4 mm (residuals from left to right: 5, 3.5, 2.6 and 2.5 mm), starting from the arithmetic mean calculated.

Looking only at the numbers, one could assume that the quality of this registration is about twice as accurate as that of the first one, although the registration parameters at hand are identical.

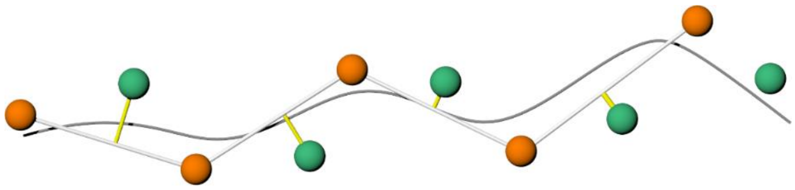


Figure 28: Formation of point-to-triangle correspondences (Wujanz 2021a)

In the next example, shown in Figure 29, the green dataset has been rotated and shifted with respect to its original position to demonstrate the effects of an inconspicuous parameter. This value is sometimes called, for example, the maximum search distance (in some cloud-to-cloud implementations), the correspondence threshold or tolerance, and, in some cases, it is adjustable in the properties of the registration algorithm applied. This parameter specifies the largest distance between two points from two different point clouds that can form a correspondence. In the following, this parameter is set at 3.0 mm. The residuals in this example (from left to right) are 12.0, 2.6, 2.9 and 12.7 mm. Consequently, two residuals are discarded because they are larger than the threshold specified, as highlighted by the two red lines. Accordingly, the "quality" of the registration is 2.75 mm. If we now apply the same parameter to the example shown in Figure 28, the quality measures "improve" from 3.4 to 2.55 mm, which is of course irritating.

In short, if this distance is set at 1 mm, the resulting quality dimension will be smaller than 1 mm.

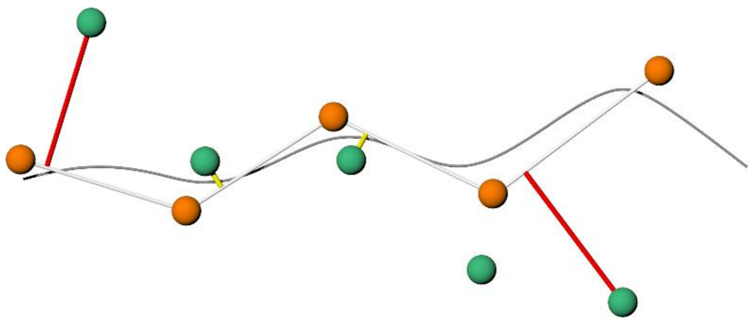


Figure 29: Formation of point-to-triangle correspondences with use of a correspondence threshold (Wujanz 2021a)

6.2.3 Block Adjustment

During block adjustment in the laser scanning context, the six degrees of freedom of all laser scanner positions registered are optimized simultaneously, therefore, depending on the initial position of the data:

- Laser scan data from adjacent laser scanner positions match
- GNSS measurements match the laser scanner positions
- Measurements from inclination sensors match the alignment of the laser scanner position
- Laser scan data match externally observed control points

As a result, a detailed report is generated. The deviations of the normal distances of plane patches of the individual scans to each other are indicated there, among other things. Reading a several-page report requires some degree of detailed knowledge.

However, in order to describe the accuracy of an entire scanning project objectively, a few control points should be both scanned by the laser scanner and measured with a measuring device of comparable or higher accuracy (e.g. a total station). The standard deviation of the residuals for these control points is finally output for an evaluation of the quality of the block adjustment. This table is generally easy to read and quickly accepted by experts.

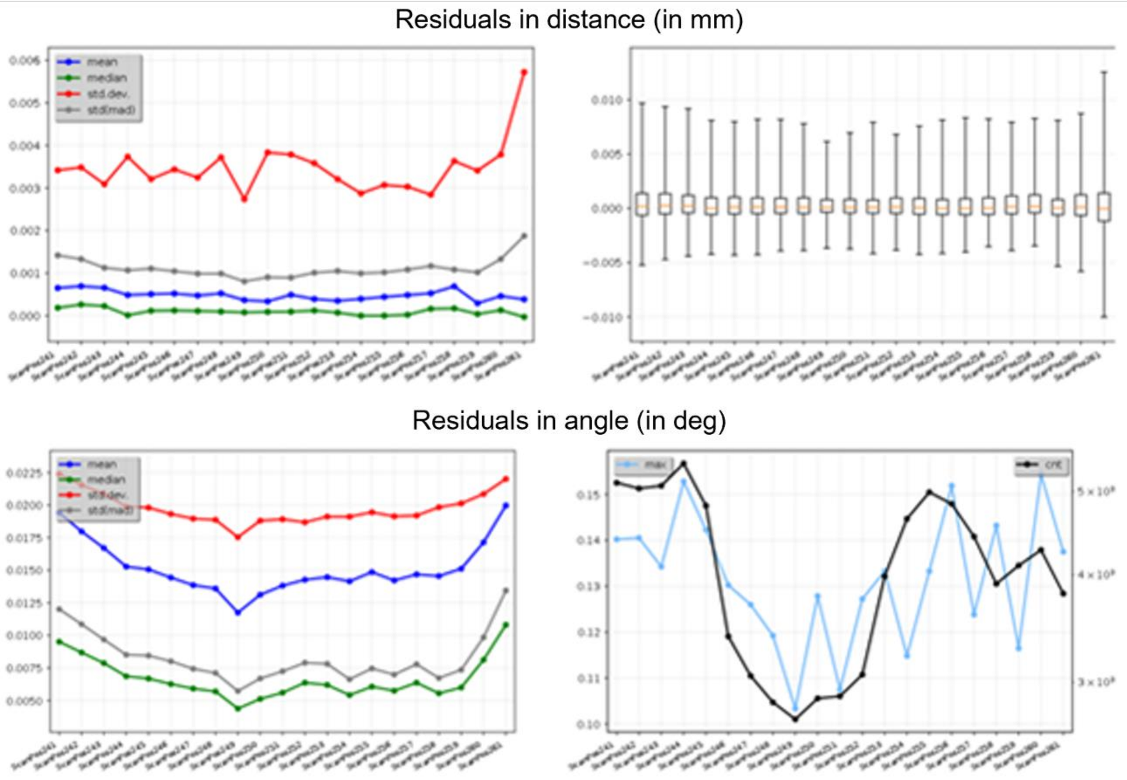


Figure 30: Example of a representation of the residuals after block adjustment

	dX [m]	dY [m]	dZ [m]	dist. [m]
Minimum deviation	-0.0041	-0.0053	-0.0095	0.0047
Maximum deviation	0.0079	0.0074	0.0101	0.0118
Mean deviation	0.0005	-0.0004	0.0003	0.0084
Standard deviation	0.0040	0.0047	0.0064	---
Median abs. dev. (std)	0.0040	0.0053	0.0075	---

Figure 31: Specification of the standard deviation of the residuals for scanned control points that were also measured by a total station. (Source: RIEGL software "RiSCAN PRO")

Figure 32 illustrates the difference between pairwise registration and block adjustment. Again, a puzzle is used as an example, with individual pieces representing individual laser scans. For the present network, the laser scans were linked in sequence so that the imperfection of the registrations creates an open polygon. The left part of the figure shows the network before loop closure. The middle part shows the last pairwise registration that should lead to the loop closure. Since the result of a pairwise registration only has an influence on two local coordinate systems, the last laser scan of the series in the form of a yellow puzzle piece is simply shifted on the first one – the existing gap or discontinuity, thus, remains. However, if one introduces all registration parameters into a block adjustment, the contradictions between all registrations are minimized, so that the desired loop closure results. If additional laser scans are added to the network, it becomes more controllable, making it easier to locate faulty registrations. In addition, the network stiffens, just as it would in a jigsaw puzzle, which improves the accuracy of the network.

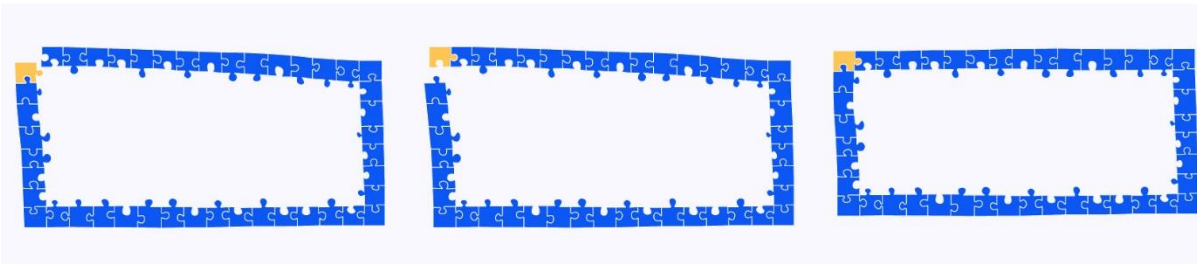


Figure 32: Penultimate pairwise registration in a "scanning network" (left), last pairwise re-registration (middle) and result after block adjustment (right)
(Liebler, i3mainz, CC BY SA 4.0 according to Wujanz 2022)

In principle, a block adjustment can be solved in two ways: via an iterative adjustment of the point clouds (Pulli 1999), which is a very error-prone solution, or by the use of the registration parameters themselves. Mathematically seen, so-called conditions are used in a block adjustment following the latter solution. A condition, which is already known from school, is that the inner angle sum in a plane triangle must always result in 180°. A common condition in surveying is used when measuring height differences, the so-called leveling. If one begins a measurement from a starting point, then this first receives a certain height. Afterwards, one determines the heights of new points and closes in a loop again at the starting point. The condition is that the sum of the positive and negative heights within such a loop must be equal to 0. Although only one degree of freedom is determined during leveling and six during registration, the same concept can be used. This means that within a loop of a laser scanning network, not only the start and end position must match but also the orientation.

6.3 Limitations of Established Quality Measures

Control points introduced with conventional geodetic measuring equipment are rightly considered the "gold standard" of quality assurance in laser scanning. Therefore, in section 6.3.1, the limits of this strategy will, firstly, be pointed out. In section 6.3.2, widely used metrics in geodesy are presented to overcome these limits, which represent an ideal supplement to the quality measures omnipresent in laser scanning.

To illustrate this, a survey was carried out with a static laser scanner as part of a tolerance check on an industrial construction site covering an area of approx. 150 x 210 m. The site was surveyed to determine the quality of the measurement. Regarding the registration of the construction site, 370 laser scans were acquired, which were linked via 528 pairwise registrations. In addition, 63 total station points were measured and connected 327 times from different positions. The accuracy requirement was 10 mm. After performing a block adjustment, the following inconsistencies were found:

- Between registrations: mean: 0.2 mm, median: 0.4 mm, max: 3.7 mm.

- To control points: mean: 3.3 mm, median: 2.7 mm, max: 7.7 mm

Looking only at the residuals to the control points, one would be inclined to assume that the accuracy requirement of 10 mm was clearly met. However, this assumption ignores two important aspects. First of all, it should be noted that, for economic reasons, not all laser scans were measured and checked tacheometrically. Thus, it is initially not clear whether all laser scans were correctly registered. Furthermore, it is not clear where the tacheometric control points are distributed in the laser scanning network and how they affect the network. Both aspects will be taken up again later in section 6.3.2.

Figure 33 shows the network configuration of the laser scanning network measured. Circles denote individual scans, while arrows represent pairwise registrations. The location of the tacheometric control points will be discussed later.

Figure 33: Overview of the measured laser scanning network

6.3.1 "Unfair Whitewashing" of Laser Scanning Networks

This section describes three simple ways in which quality assurance can be calculated "nicely." It is irrelevant whether static or kinematic laser scans are processed. Let us assume for the present example in the following that contradictions to the tacheometry over 10 mm are present.

The first strategy is based on the targeted reduction of redundancy with the focus on the geodetic control points. This is done by simply resolving all point identities between tacheometry and laser scans that exceed the value required. In the left part of Figure 34, red triangles indicate disabled control points, while green triangles highlight the control points used. It is obvious that it is easy to achieve "accuracies" around 1 mm as long as you keep sorting out points. The consequence is a general destabilization of the network, which usually leads to extrapolation effects. None of the negative influences are reflected in the resulting residuals. These continue to suggest a highly accurate result.

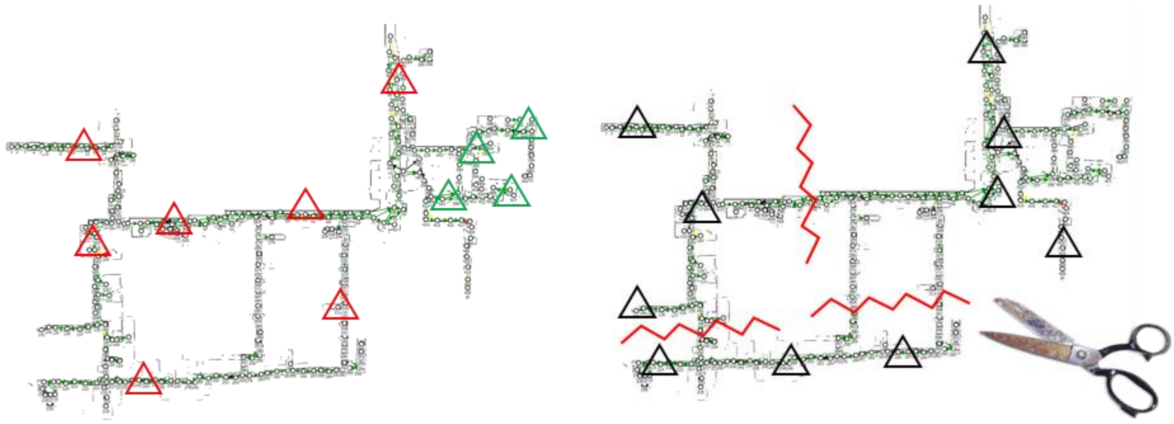


Figure 34: Reduction of control points (left) and registrations (right)

In the second strategy, redundancy within the network is also deliberately reduced, but now by breaking up pairwise registrations or splitting kinematic laser scans. If tensions occur in the network that have a negative effect on the contradictions at the control points, they can be separated either between two control points or alternatively within an existing loop. The result of this method are single blocks of connected static and/or kinematic point clouds, which are connected to the geodetic datum via at least three control points per block. Again, the resulting contradictions after a "successful" application of this method pretend to be a sufficiently exact result. The consequences are unclean transitions between the individual blocks. It should be mentioned that this effect also occurs unconsciously in many commercially available software solutions for the registration of static laser scans, i.e. when the software is not capable of adjusting larger scan projects together. In this case, the projects are either divided into subprojects that can still be processed or groups or so-called clusters. The right part of Figure 34 visualizes the method mentioned. Triangles again indicate geodetic control points, while the red zigzag lines represent the separation points of individual blocks.

A third method of unfair influence on the results is inadequate weighting. It is worth mentioning here that in many software solutions, this manipulation is not deliberately induced by the user but by the manufacturer in the form of fixed weights of individual observations. To illustrate this method, we start from a kinematic scanning project. Using GNSS, control points were measured in an outdoor area. Their accuracy is known to be significantly lower than that of tacheometric observations. In order to obtain small residuals at the control points, one chooses, for example, *a priori* weights of the GNSS points in the submillimeter range, while the contrasts between the two data sources are pushed into the laser scanning network. The more optimistic, i.e. higher, the accuracy is assumed, the greater the constraint exerted on the network. As a result of this, the point cloud is bent. This is sometimes seen in projects with GNSS control points whose height accuracy is noticeably worse than that of the location, in the form of non-planar floors.

6.3.2 Geodetic Quality Measures in Laser Scanning

It is not for nothing that there are quality measures in geodesy beyond the residuals. Therefore, suitable measures and their significance are presented in the following. The introduction of geodetically coordinated control points is, as has been said, a reliable method to check, for example, the referencing of static laser scans. However, it would be uneconomical to measure every single laser scan. Therefore, to bridge control points, numerous commercial solutions are available to register laser scans based on their overlap areas. One solution frequently used in practice for this purpose is the ICP algorithm (Besl & McKay 1992).

However, partial redundancies can be calculated to protect against the unfair methods presented earlier. These give information about the degree of the controlledness of the pairwise registration parameters. If two laser scans are only connected by one registration, the partial redundancies are zero. Such a scenario must be avoided at all costs, because no reliable statement can be made about the correctness of the registration result. In Figure 35, the partial redundancies have been calculated for the example network. Green arrows indicate good redundancy, while red arrows indicate weak redundancy. Measures to control the two registrations would be the calculation of another pairwise registration (if the measurement configuration allows this) or the introduction of a geodetic control point at the dead end of the traverse. Another reason for low partial redundancies is the geometric nature of the overlap area between two laser scans. Let us assume there is a cylindrical tunnel. Even if the laser scans acquired were integrated with more than one registration, both the translation along the tunnel axis and the rotation around it are only weakly determined. Partial redundancies provide information about how trustworthy and resilient the quality measures derived, for example, residuals, are.

In order to show the consequences of the thinning of redundancy, stationing accuracy is suitable as a criterion. This provides information on how accurately a static laser scan or parts of a kinematic scan could be positioned with respect to a geodetic datum. The datum can be, for example, local coordinate systems of individual scans, geodetic control points or a planning model, such as a CAD or BIM. Uncertainty propagation can be used to calculate the stationing accuracy for each laser scan or partial scan. The quality of the stationing depends on many factors, but is, therefore, also meaningful. Influences are, for example, the total network configuration of the pairwise registrations, the quality and position of control points, the individual weighting of the observations and the quality of the calibration of the laser scanner used.

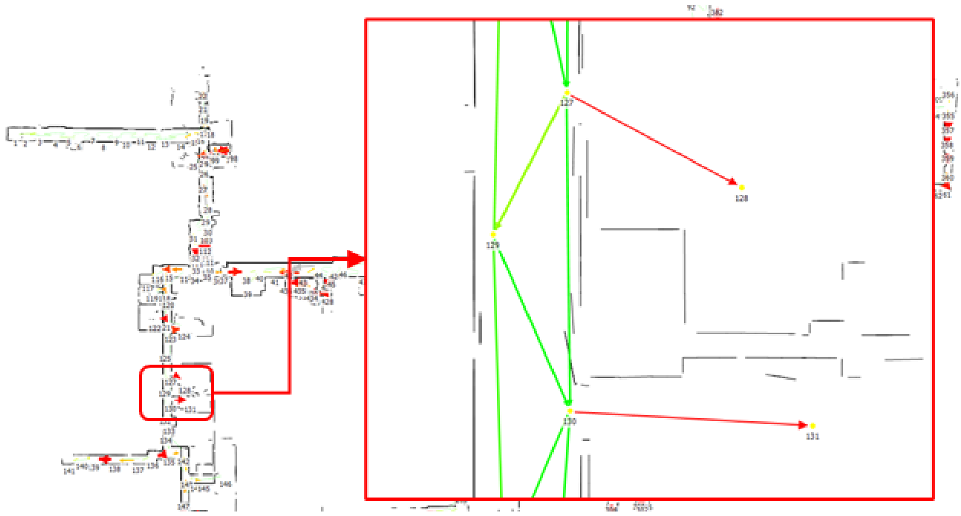


Figure 35: Partial redundancies of a static scanning network

If one calculates the stationing accuracy for the example introduced at the beginning of the section, it becomes apparent that the accuracy of 10 mm required cannot be met. This can be seen from the coloring in the right part of Figure 36. Scans colored in red show a stationing accuracy above the accuracy required. This seems strange, at first, when considering the mean residuals of 3.3 mm to the tacheometry, but becomes plausible when the position of the tacheometric control points is taken into account. This is highlighted by the blue polygon. It is obvious that the distribution of the control points was chosen in an unfavorable way. The extrapolation errors which have occurred can be traced in the left part of Figure 36 by means of a puzzle.

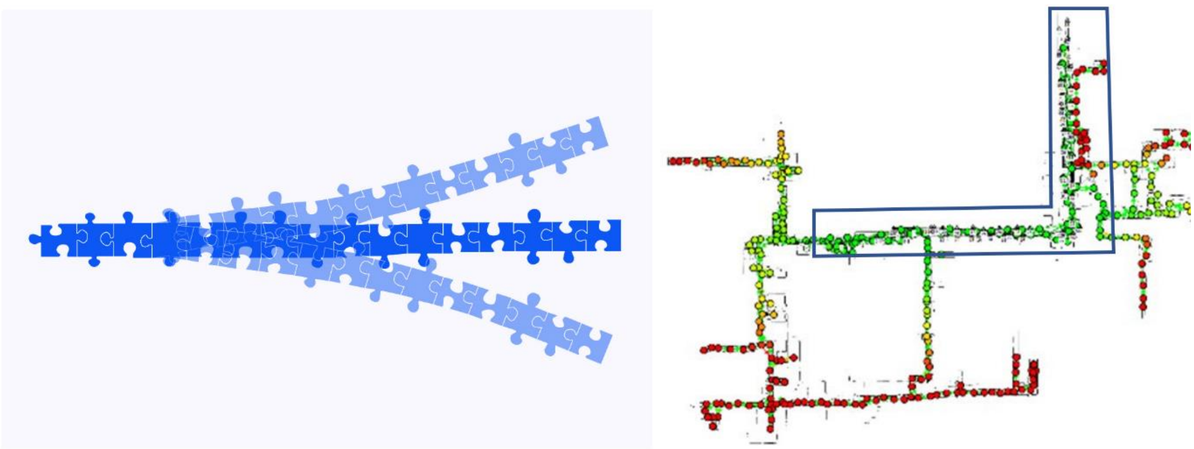


Figure 36: Uncertainty propagation of a puzzle (left) and a laser scanning network (right)

6.4 Visual Inspection

A visual inspection of the composite point cloud should be done before exporting it to another software. It is recommended to display the point cloud in the orthogonal projection (also with parallel sight rays) and to view a cross-section. The following figure shows the points marked in the top view of a bridge. Below, only these points were shown from the horizontal view along the bridge axis. You can see here that the laser scans match each other sufficiently well.

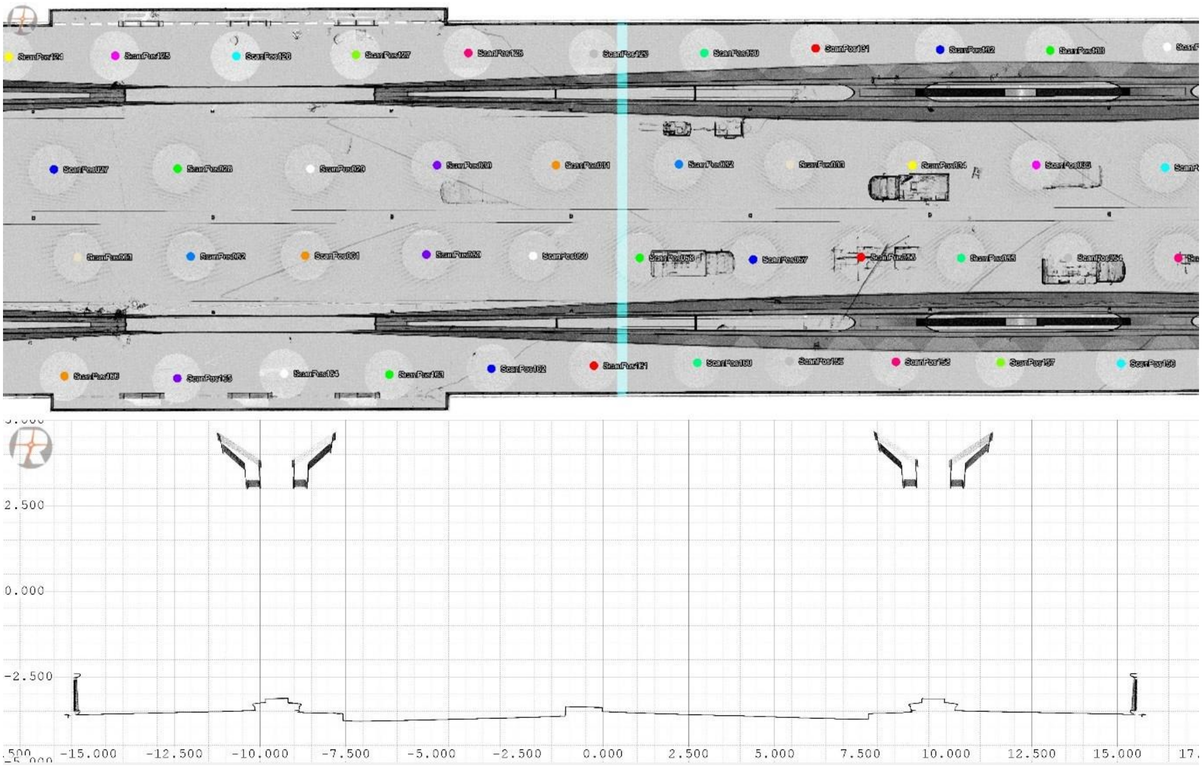


Figure 37: Visual inspection of a bridge scan: the top view of the scanned bridge with marked points (top) and the horizontal cross section of the points along the bridge axis (bottom).

On this occasion, the calibration of the photo camera can also be checked. The point cloud is superimposed on the photo and the exact alignment is checked on suitable objects, such as the border of the footpath.

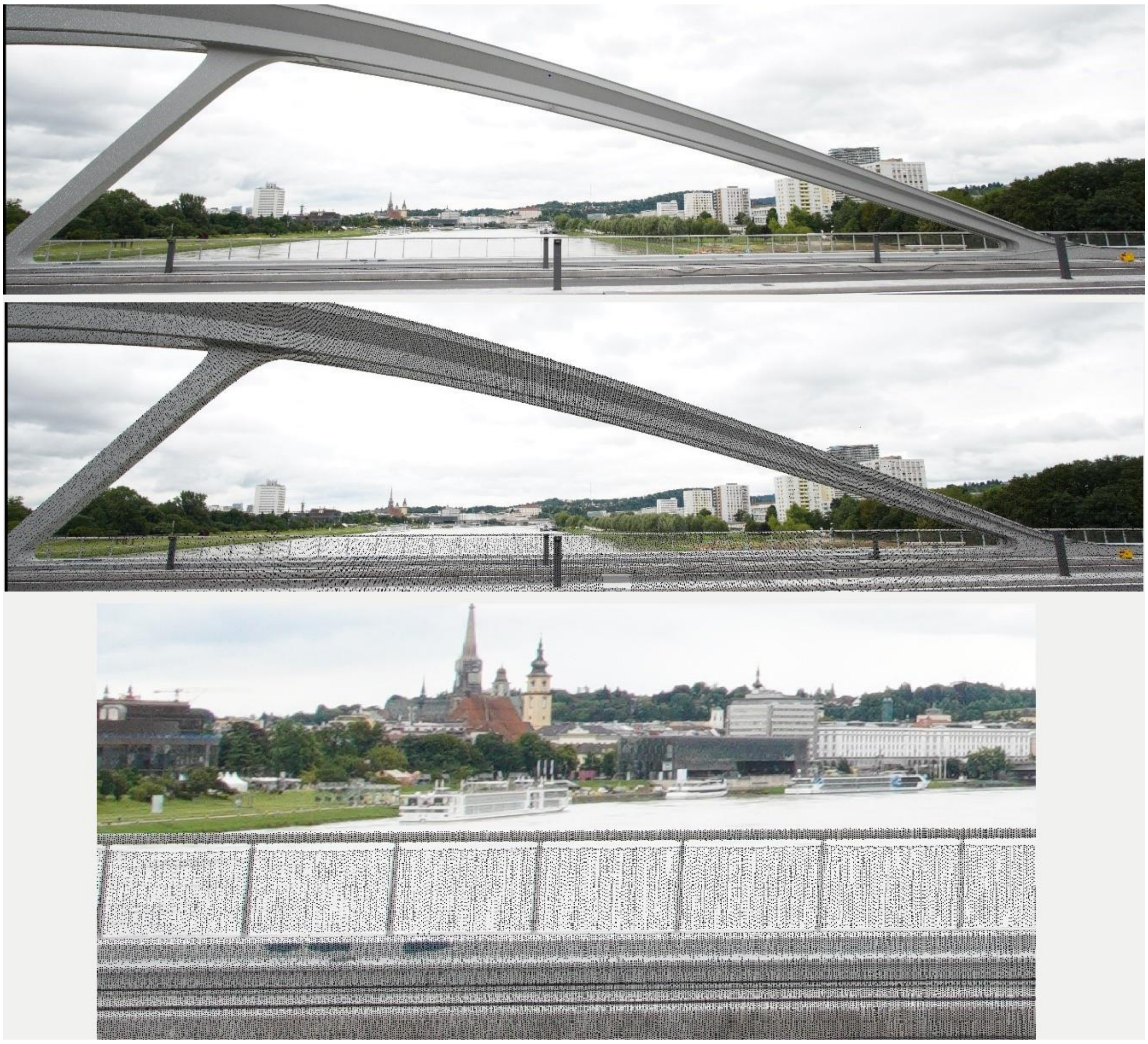


Figure 38: Visual inspection of the (extrinsic) calibration of the camera: photo (top), photo with overlaid point cloud (middle), detail of the photo with overlaid point cloud (bottom)

7 Best Practice

Before taking up scanning projects professionally, you should have familiarized yourself with the measurement technology and the customer requirements. The first projects should be as small as possible so that you can train your best process and correct it if necessary. Experience gained over time then empowers you to take on larger projects. Of course, the details vary from person to person and from scanner to scanner. The following summary is, therefore, only a suggestion.

7.1 Accessories and Preparatory Measures

Before starting a scanning project on-site, you should ask yourself the following questions:

- Which tripod is appropriate (a lightweight indoor tripod with rubber feet or an outdoor tripod with pointed feet)?
- How many laser scanner positions are likely to be needed for the project? This will determine the estimated time of use and the number of batteries required. Around 80% of all scanning problems are discharged batteries.
- A prior walk-through of the area to be scanned has the advantage that you can orientate yourself afterwards. On the other hand, you lose precious (scanning) time. It is advisable to take a second person with you, especially for very large projects. This way, you can separate organizational tasks and scanning activities.
- Before scanning, you should know as precisely as possible the results of the measurement required. Especially the accuracy of the scan project required, the delimitation of the scan object and the resolution of the point cloud can be decisive. "As accurate as possible" or "the highest resolution on the object" are often not useful.

It is recommended to develop a checklist that could look something like this:

Table 3: Check list for the preparation of a measurement campaign

Equipment	**Remark**
Laser scanner	Cleaned and ready for use
Batteries	For example, 6 batteries, charged
Charger	With multiple sockets, so that the discharged batteries can be charged on-site during scanning
Tripod(s)	For outdoor measurement: a classic survey tripod with spikes; for indoor measurement: a lightweight carbon tripod with rubber feet.
Camera	For documentation purposes, and for coloring the point cloud
Mobile phone	Charged, possibly with power bank, also to document the project as an aid for the subsequent processing of the data
RTK GNSS antenna on laser scanner	If necessary for this project; base station or correction data via internet

7.2 Scanning Strategy

It is advantageous on-site to select the first scan position outdoors. This normally ensures georeferencing with an attached GNSS antenna.

If fiducials are used (for a reference measurement with a total station), these should be attached **before** scanning, possibly already observed by geodetic means. Only in exceptional cases can they be remeasured later by the laser scanner.

If it is a free-standing building, it is advantageous to select the first scan positions around the building.

Outdoors, the rule of thumb is: one scan position every 10 meters, with a distance from the facade of about 10 meters. Of course, this depends on the size or height of the building. Inside, the distances are correspondingly shorter.

The overlapping area between the scan positions should be large enough to ensure robust registration of the scan data. If this is not ensured, one can lose a multiple of the time that an additional scan position would have cost in the office for a successful registration.

If a facade plan is to be made at a scale of 1:100, a point spacing on the object of about one centimeter should be aimed for. This defines the measurement program and the distance between the scan positions.

A good ratio between scan time per scan position, resolution on the object and the number of scan positions should be selected. It is not advantageous to take extremely high-resolution scans from a few scan positions. It is better to have a few more scan positions with a slightly lower point resolution on the object. This will minimize scan shadows.

When scanning the interior of a building, it is recommended to enter the building through one entrance, scan one scan position at a time, and leave through another exit. The most important scans are those performed in a doorway. They measure half of the previous room and half of the next room. These overlapping areas of the scans are of great advantage for registration. Care should be taken to ensure that the scan shadows under the laser scanner are completed by the next scan position.

If you reach a dead end (e.g. the end of a tunnel), you should return to a position that is already known (i.e. a scan position that has already been registered or one that is easy to register) and continue scanning there. These scan positions can also be called "anchor positions." If not supported by the scanner firmware, it is recommended to take a small notebook with you and document these large jumps in the sequence. It may also be possible to document them with photos taken with the cell phone.

With regard to taking photos, it is generally recommended to take manually exposed photos. This ensures that all photos are exposed in the same way. The following parameters should be observed: exposure time, aperture, ISO sensitivity and white balance. It is sometimes advisable to scan at night under artificial lighting with a long exposure time, because, in this case, constant exposure conditions can be achieved over an entire project.

If the scanning takes place over several days, it is advisable to select the first scan position of the following day following the last position of the previous day. In this way, it is easier and clearer, in most cases, when the scan projects are combined later.

If possible, scanning should be done at times when the site is deserted, otherwise all "moving targets" will have to be removed from the scan data afterwards (see Section 3.3).

7.3 Processing Major Projects

The definition of a "large project" is manifold and very different for many users. We will limit ourselves here to projects that have to be acquired over several days and consist of several hundred scans. It is advisable to proceed strategically here and create your own checklist:

Table 4: Checklist for the processing of major projects

What results are to be generated from the project?	Point cloud, plan generation from point cloud, 3D BIM model, ...
How many resources are available for scanning?	Number of scanning days, number of people, number of laser scanners, ...
Is the survey of control points required?	If yes, are they measured **beforehand**? How are they signaled? Are they well distributed across the project?
What is the infrastructure like on-site?	Is it possible to charge batteries? Do you have a lockable room for measuring equipment? ...
Are there plans existing already?	An overview plan facilitates orientation on-site. Marked control points can be taken into account.
What resolution of the point cloud is required or is reasonable?	From this, one can estimate an average distance between scan positions. The average distance to a facade to be measured can also be determined.

The decision regarding which laser scanner positions to choose on which days often resolves itself. Nevertheless, scan positions can frequently be combined. In the case of a cathedral survey, for example, the following areas can be processed separately: outside the cathedral square, church room, attic, cellar or catacombs. In the case of transitions from one area to another, it is advisable to carry out a sufficient number of connection scans and, if possible, to fix their position using control points.

Another interesting example is the survey of a town center with many streets. Here, the scans of the street intersection areas can be measured with control points and "frozen" so that the registration of scans can then be carried out relatively quickly from intersection to intersection.

When scans are "frozen," they remain unchanged in terms of their location and orientation, while all other scans must fit into this rigid framework. This approach is not only useful for very large projects but also for deformation measurements.

The maximum number of scan positions depends mainly on the post-processing software and computer. In most cases, there is no concrete information on this. It is recommended to increase the scan positions slowly from project to project. The individual processing steps from 1000 scan positions take a considerably long time. Here, a high degree of automation of the software becomes increasingly important. Most of the time is lost in manual work, such as manual registration of too few laser scans or manual cleaning of scans (e.g. because of reflections and moving objects).

It is strongly advised to register all scans in a project and perform block adjustment. However, sometimes this is not possible due to the size of the scan project.

7.4 Working with Groups or Clusters

When processing complex projects or those with a large number of scans, it makes sense to divide them into groups or so-called clusters. A project in building construction would typically be divided into individual floors, staircases or other architectural units, which are then processed sequentially. Once all units of a project have been processed individually, the final task is to combine all groups or clusters into a cohesive data set. Finally, it is essential to perform a final block adjustment in which the contradictions of all the scans involved are minimized. It should be noted here that not all software solutions can really solve this task. If this is not the case, scans are usually optimized within a group and then the individual groups are optimized with respect to each other. A major disadvantage of this approach is that the inner geometry is kept within a group. This means that these scans are treated like an unchangeable single scan. Consequently, this approach results in inevitable stresses at the group boundaries.

This effect is illustrated in the left part of Figure 39, where two clusters can be seen. Since the inner geometry of the clusters is captured, the stresses mentioned occur at their boundaries. If the scans are block adjusted, all scans are allowed to "move" and the total contradictions within a project are optimized, as can be seen in the right part of the figure.

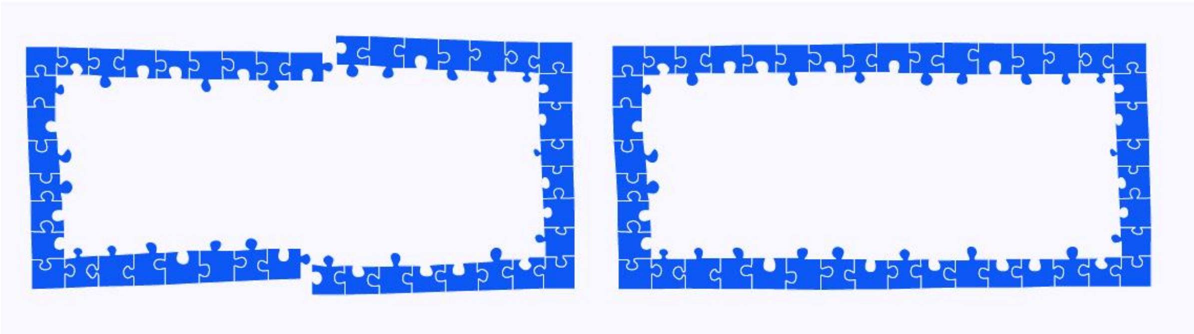


Figure 39: Cluster optimization (left) vs. block adjustment over all scans (right). (Liebler, i3mainz, CC BY SA 4.0)

Therefore, one should always find out exactly which strategy the software used employs. If the software only performs cluster optimization, the cluster boundaries should be strategically placed so that any visible transitions in the final point cloud registered lie in noncritical areas.

7.5 Connection to Superordinate Reference Systems

So far, we have learned about several coordinate systems:

- The coordinate system describes the coordinates of the individual laser scans from a laser scanner position. Originally in polar coordinates, they are usually stored as cartesian coordinates. In most cases, the origin of the coordinates is located in the laser scanner and defined in the respective operating manual.
- The project coordinate system describes the coordinate system of a laser scanning project, which consists of several laser scanner positions. The laser scanner coordinate system of the first position usually defines the project coordinate system.
- A superordinate coordinate system makes it possible to relate several laser scanning projects to each other. The GNSS measurement of the laser scanner positions usually transforms the projects into the WGS84 coordinate system. Its coordinate origin lies in the center of mass of the reference ellipsoid chosen as a model of the earth. The registration as a connection to a superordinate, absolute coordinate system is called georeferencing.

The EPSG code is a system of worldwide unique codes for coordinate reference systems and other geodetic data sets, such as reference ellipsoids or projections. Information on the EPSG codes is available in an online database (epsg.org).

In principle, there are three reasons for connecting the laser scans registered to superordinate reference systems:

1. Transfer to target coordinate systems
2. Stabilization of the laser scanning network
3. Increase of redundancy/independent control with another measuring device.

Transformation to Target Coordinate Systems

When laser scanning projects are handed over to the respective customer, a specific target coordinate system is usually complied with in addition to the delivery format. The term target coordinate system can be interpreted in many ways and can mean, for example, local construction site or ship coordinate systems, national or global systems, or plant coordinate systems. In principle, this means that the laser scanning network is transformed with the aid of control points, which must be available in both the target coordinate system and the laser scanner coordinate system. In practice, the average size of the point residuals after the transformation is often referred to as a quality measure. However, this figure is only of limited significance since the position of the points used has a significant influence on the size of the point residuals.

Glossary

Three-dimensional laser scanning is the controlled deflection of a laser beam in conjunction with a laser range finder in numerous directions. This method, often referred to as 3D object scanning or 3D laser scanning, provides point clouds that describe the surfaces of the object scanned. Depending on the laser scanning system, the deflection of the laser beam can be performed at coordinated rotation rates of the deflecting rotational axes and, thus, provide a regular point raster or at mutually arbitrary rotation rates. A distinction is made between static measurements (see also TLS) and measurements with a moving laser scanner (kinematic laser scanning). Compared to kinematic laser scanning, static laser scanning is slower but also more accurate.

Absolute orientation: In photogrammetry, the absolute orientation establishes the relation to a superordinate coordinate system, e.g. a national coordinate system or a coordinate system that can be defined by control point coordinates.

Accuracy: The accuracy of a laser rangefinder is the degree to which the distance measured approximates the actual (true) distance of a target. Accuracy is not to be confused with precision.

Amplitude: The amplitude of the echo signal reaching the laser scanner depends on a number of parameters, including system parameters and target parameters, such as reflectance and target distance. Through careful calibration, some laser scanners provide an amplitude value for each echo signal detected that reflects the amplitude of the optical echo signal. The amplitude is relative to the amplitude of an echo signal at the detection threshold of the device.

Beam diameter: The beam diameter of a laser beam is the diameter perpendicular to the beam axis. Since beams typically have no sharp edges, the diameter can be defined in many different ways, for example, with the $1/e^2$ definition, which is common for so-called Gaussian beams, i.e. those with a Gaussian-shaped power density distribution. The power density at a distance of half the beam diameter from the axis has decreased to a $1/e^2$ fraction of the maximum power density on the beam axis. There are also the following definitions: $1/e^2$ full angle, $1/e$ full angle, $1/e^2$ half angle or FWHM ("full width at half maximum").

Block adjustment: The term block adjustment in the TLS context refers to the overall adjustment of all related point clouds previously registered in pairs to determine the 6 degrees of freedom, taking into account all additional available information (e.g. GNSS or inclinometer measurements, control point coordinates). Assuming calibrated laser scanners, the block adjustment in the local coordinate system assumes the degree of freedom of the scale to be constant.

Bundle block adjustment: The bundle block adjustment (also called bundle triangulation) is an adjustment method originating from photogrammetry for the simultaneous orientation of camera images arranged arbitrarily in space. The coordinates of object points, which are mapped in several images and, thus, can be measured as corresponding points, serve as observations. The results of the calculation are, in addition to the orientation parameters of the images, the coordinates of the object points and possibly further modeled parameters of additionally integrated measuring systems.

Diffuse reflection: Diffuse reflection is the reflection of light at a surface. An incident beam is reflected uniformly in all directions. Lambertian reflection is often used in LIDAR as a model for diffuse reflection. Rough surfaces (roughness on the order of the laser wavelength), e.g. rough masonry, can be well modeled as diffuse reflecting targets. A retroreflective target is a target with a high directivity of the reflected laser radiation. Examples of retroreflective targets are reflective foils, traffic signs and "cat's eyes."

Echo signal (pulse time-of-flight method): Similar to acoustics, where an echo refers to a reflection of sound from a distant object, the echo signal in laser scanning is the reflection of the emitted laser pulse that arrives at the laser scanning device with a delay, the time-of-flight. The term echo signal can refer to the optical signal that arrives at the device, but also to the electrical signal within the receiver electronics of the device.

Eye-safe wavelength: Optical radiation above 1400 nm wavelength is absorbed over a large area in the cornea. It provides protection for the retina of the eye. Consequently, the wavelength range from 1500 to 2000 nm is also called "eye-safe." Invisible laser light with a wavelength of 1550 nm (fiber laser, Er-doped) has become widely used in laser scanning.

Georeferencing: Georeferencing is the transformation to a superordinate, absolute coordinate system, and is, therefore, a special type of registration.

ICP: The iterative closest point algorithm (also called "Cloud2Cloud") is a registration algorithm that works without targets or extracted feature points. The prerequisite for this is a prealignment that has already been done, which can be derived either manually, from other algorithms, or from sensor observations. This method aims at minimizing the distances of overlapping parts of the point cloud by varying the position and rotation of the data set to be adjusted. The algorithm optimizes the relative position and orientation of two data sets in an iterative process. This process ends when a convergence criterion is met.

IMU (inertial measurement unit): An IMU consists of its combination of multiple accelerometers and angular rate sensors. In some cases, an IMU is supplemented by magnetometers. The IMUs are used for motion detection.

Laser class: Laser classes are used to evaluate the safety of laser instruments. A distinction is made between four laser classes, which assess the hazard potential in the gradation 1 to 4. Laser class 1 means: safe, laser class 2 means: the accessible laser radiation is only in the visible spectral range (400 to 700 nm). It is also harmless to the eye if irradiated for a short time (up to 0.25 s).

Laser radar cross-section (LRQ): The laser radar cross-section is a target property. It is useful for calculating the echo signal amplitude expected when the system parameters and the target distance are known. The LRQ is the product of three components: the actual area interacting with the laser beam (for targets smaller than the laser footprint), the reflectance of the target and the directivity of the reflection. The directivity is quite low for diffusely reflecting targets, but very high for retroreflecting targets.

LIDAR (light detection and ranging): LIDAR Is a method for optical distance measurement.

Point cloud: An unsorted set of points with coordinate values in a defined coordinate system, e.g. acquired by laser scanning. In addition to geometric information (coordinate values), a point cloud usually also contains radiometric information in the form of intensities (cf. radiometry) and optionally color values from passive cameras, which can be used for visualization. Furthermore, it can contain information such as a time stamp, amplitude, reflectance, pulse shape deviation or signal-to-noise ratio.

A point cloud unfolds its information content only in the context of other points – the observation of a single point does not lead to any gain in knowledge.

Precision: The precision of a measurement system is the degree of mutual approximation between the results of measurements made successively under the same measurement conditions. Precision is not to be confused with the accuracy of a measurement.

Preliminary alignment: Determination of approximate values of the registration parameters, which allow a subsequent registration (e.g. by means of ICP). As the name suggests, the results obtained are not accurate enough to be considered as final results.

Pulse shape deviation: The so-called "pulse shape deviation" can be obtained by echo digitization and waveform processing by digital signal processing. In addition to the target width and amplitude, the pulse shape of the echo signal is compared with the pulse shape, which represents the so-called system response. The pulse shape deviation is one of the additional attributes of each point of the point cloud. Low values indicate that the impulse shape of the echo signal is not significantly different from the system response. High values indicate echo signals with a significantly different pulse shape, which may be caused, for example, by the merging of echo pulses from multiple targets that were hit by the laser beam at only slightly different distances. The pulse shape deviation can, thus, be regarded as a quality measure for the reliability of a single measurement. An upper bound for the maximum permissible deviation is often selected in automatic filtering.

Radiometry: In addition to geometric information, laser scanners acquire so-called radiometric information. While (passive) photo cameras determine gray values based on the intensity of reflected sunlight, laser scanners measure the reflected signal strength in the narrowband wavelength range of the laser diode. The signal strength depends mainly on the imaging configuration, atmospheric conditions and surface properties of the object. Radiometric quantities are also called intensity or reflectance and add visual information to geometric information.

Reflectance: Reflectance is a target property and refers to the fraction of incident optical power that is reflected from that target at a given wavelength. The reflectance is always a positive real number. Some laser scanners provide a reflectance value for each target detected as an additional attribute. The reflectance delivered is a ratio of the actual amplitude of this target to the amplitude of a white, flat target in the same area, oriented orthogonally to the beam axis and whose size is larger than the laser footprint. The actual reflectance value is given in decibels (dB). Negative values indicate diffusely reflecting targets, while positive values usually represent retroreflecting targets.

Registration parameter: The result of a registration or referencing is usually six numerical values, three translations (along the x/y/z axes) and three rotations (about the x/y/z axes), which describe the mathematical transformation from the starting coordinate system of a point cloud to a target coordinate system. If another laser scanner is to be added, for example, for detailed images or georeferencing, "the scale" should also be considered as a degree of freedom.

Relative orientation: A relative orientation in photogrammetry describes the relation between two local image coordinate systems. Relative orientation opens up the possibility of measuring 3D coordinates in two-dimensional images. However, the resulting coordinates are still unscaled and, thus, not metric. Finally, therefore, the absolute orientation is carried out, which finally allows the measurement of scaled coordinates.

Residuum: The remaining deviation of an observation to the estimated model after an adjustment.

Retroreflection: Reflection mainly in the direction of the incident laser beam (also called the cat's eye effect). Traffic signs and cat's eyes on bicycles have retroreflective properties.

SLAM (simultaneous localization and mapping): This is a computer vision or robotics method for automatic navigation. A robot, for example, creates a 3D map of its environment and simultaneously determines its own current position and orientation within this environment.

Specular reflection: The reflection of light beams on a smooth mirror (or glass pane) is called direct or specular reflection. This deflection of laser beams is undesirable in laser scanning because the resulting point cloud does not contain the mirror surface. Instead, the surface of the mirrored object falsely appears behind the mirror surface in the point cloud.

Terrestrial laser scanning (TLS): A laser scanner systematically scans its surroundings from its static position by deflecting the emitted laser beam vertically with a rotating mirror and horizontally by rotating it about the standing axis of the laser scanner. At the same time, the distance to the object surface scanned by the laser beam is measured using electrooptical distance measurement techniques. In this way, hundreds of thousands up to millions of measurement points are acquired per second. This controlled deflection of a laser beam, thus, takes place in the form of a raster in the polar coordinate system. The TLS provides point clouds that describe the surfaces of the object scanned. In most cases, the laser scanner is mounted on a tripod, but it may also be mounted, for example, on a stationary vehicle.

Time-of-flight (TOF): The time it takes for the transmitted laser pulse to reach the target surface plus the time it takes for the echo signal to reach the receiver of the laser scanner. The distance to the target is calculated in the TOF laser range finder from the pulse travel time, based on knowledge of the velocity of the pulses in the air (propagation medium).

Transformation parameters: See registration parameters.

Voxel: A voxel is a cubic volume element. It is used to structure 3D data sets (point clouds). The 3D space is divided into individual cubes. The edge length of these cubes depends on the target and the distribution of the data in the 3D space. The amount of data enclosed by a voxel is assigned to it.

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