Survey Configuration for Terrestrial Laser Scanning

Aufnahmekonfiguration für Terrestrisches Laserscanning

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Despite the enormous popularity of terrestrial laser scanners in the field of geodesy and related sciences the vital task of viewpoint planning is mostly considered intuitively. In contrast to established acquisition techniques, such as tacheometry and classical photogrammetry, optimisation of the acquisition configuration cannot be conducted based on assumed object coordinates, as these would change in dependence to the chosen viewpoint. Hence, this article discusses on how laser scans can be simulated based on predefined viewpoints and a given 3D model. Afterwards the task of viewpoint planning is observed from two perspectives namely regarding the achievable precision in the field as well as from an economic point of view in the context of data acquisition.

Keywords: Terrestrial laser scanning, viewpoint planning, survey configuration, ray casting, economic considerations, engineering geodesy

Trotz der enormen Popularität von terrestrischen Laserscannern in der Geodäsie und benachbarten Fachdisziplinen wird die grundlegende Aufgabe der Standpunktplanung zumeist intuitiv gelöst. Im Gegensatz zum Vorgehen bei etablierten Erfassungsmethoden wie Tachymetrie und klassische Photogrammetrie, kann die Optimierung der Aufnahmekonfiguration nicht anhand fest vorgegebener Objektkoordinaten erfolgen, da sich die Punktverteilung beim Laserscanning in Abhängigkeit vom gewählten Aufnahmestandpunkt ändert. Daher wird in diesem Beitrag zunächst aufgezeigt, wie Laserscans unter Verwendung eines 3D-Modells des zu erfassenden Objekts sowie vorgegebener Standpunkte simuliert werden können. Danach wird die Aufgabe der Standpunktplanung von zwei Seiten betrachtet, nämlich in Bezug auf die erreichbare Genauigkeit sowie unter ökonomischen Gesichtspunkten im Zusammenhang mit der Datenerfassung.

Schlüsselwörter: Terrestrisches Laserscanning, Standpunktplanung, Aufnahmekonfiguration, Raycasting, ökonomische Gesichtspunkte, Ingenieurgeodäsie

1 INTRODUCTION

Nowadays terrestrial laser scanning (TLS) is a very popular and widely used methodology in geodesy, civil and mechanical engineering, architecture and beyond. A lot of publications to various problems of TLS methodology and applications exist, e. g. scanning of radio telescopes /Holst et al. 2015/ or dams /Eling 2009/, /Wang 2013/. One laser scanner viewpoint provides a spherical representation of its surrounding in a local coordinate system with the centre of the scanner as origin. Multiple scans from different viewpoints are required to get full coverage of all object surfaces and to avoid occlusions. The optimal placement of these viewpoints (locations of instrument set-up) for a precise, complete and reliable acquisition has hardly been investigated; the solutions in practice are mostly based on intuition and experience. This is astonishing as this issue is relevant for regularly conducted engineering surveys, as preparatory measures before expeditions or other survey campaigns, where the length of stay is restricted, critical or costly.

In network theory this problem is referred to as "configuration problem", where e. g. solutions can be found for acquisition methods using total stations /Niemeier 2008, 331 ff./, /Ghilani 2010, 455 ff./, levelling /Holst 2015/ and images/photogrammetry /Luhmann 2011, 446 ff./. In this context often criteria like equal point distribution and homogeneity of point precision are discussed, e. g. to set-up an area-wide control network, or a specific target function has to be fulfilled by the network, e. g. to achieve a specific precision in one direction for monitoring tasks. However, a direct transition of the described procedures onto TLS is not applicable as all cases assume discrete, repeatedly observable points in object space while only the acquisition configuration is optimised. This case is not given in terrestrial laser scanning as the point sampling on the object's surface is directly dependent to the chosen viewpoint. Consequently observations have to be simulated for all potential viewpoints – this procedure is referred to as ray casting /Appel 1968/ and will be discussed in Section 3. It should be mentioned that the term photogrammetry strictly refers to engineering photogrammetry where discrete markers need to be brought into object space. Novel developments such as dense image matching /Wenzel et al. 2013/ do not require markers and hence face the same issues as TLS.

The general task of TLS acquisition is to derive a complete 3D model of the study object, which might be a complex structure. The captured 3D point cloud is a first step for more detailed modelling approaches, which are beyond the topic of this paper. Often requirements are pre-defined for the precision of all or the main object points respectively surfaces and for the completeness of the achieved information. Existing solutions of the configuration problem based on classical geodetic instruments can be categorised into economic approaches and ones from that follow the perception of engineering geodesy. As a consequence the structure of this article will stick to these categories. It has to be explicitly mentioned that the survey configuration influences the resulting outcome in numerous ways that are beyond the scope of this article. Thus, this article focuses solely on chosen aspects that are of particular relevance for the field of geodesy and related sciences. In particular the impact of the survey configuration onto:

- the identification of minimal viewpoint sets (Section 4),
- the achievable accuracy (Section 5.1),
- the estimation of unknown parameters (Section 5.2),
- the detectability of deformations (Section 5.3)

are thoroughly discussed. A look at the previous list reveals that a distinct decision on what an optimal survey configuration is cannot be drawn. This argument can be justified by the fact that optimality may be defined by either a single criterion, a combination of several or all mentioned criteria. In practice the most common task has the objective to complete a survey campaign with minimum efforts, i. e. with a minimum number of TLS-set-ups, as each extra TLS-position means extra acquisition time and additional costs.

2 REQUIRED PRE-INFORMATION FOR VIEWPOINT PLANNING

As mentioned earlier several pieces of information are required in order to determine an optimal survey configuration. In addition a precise definition of the desired deliverables needs to be conducted. For the actual simulation of laser scans geometric information of the object of interest as well as detailed knowledge about the applied TLS is needed. Hence for viewpoint planning, several questions and considerations have to be handled.

2.1 Project requirements

What are the geometrical dimensions of the object? Is it a single structure, where e. g. internal (indoor) and external (outdoor) information is needed? The geometrical extent can vary between 20 – 50 m for single buildings up to 500 m or more for a complete ensemble of buildings or an engineering structure (concrete dam, bridge) or an artificial slope or landslide effected area. What is the final objective of the TLS capture? Is it to derive a rough 3D/2D model for facility management, property evaluation or sales activities or to derive a complete 3D model with high resolution and precision? Is it necessary to capture selected facades with extremely high precision and resolution? Can some remote areas of the object be neglected?

2.2 Object information

Pre-information on the object under consideration is an absolute must for solving the configuration problem. This pre-information is at least a manual sketch/drawing of the objects with some scale information. Sometimes a simple 2D plan of objects exists, e. g. from design or construction phase. Preferably geometric information should be given in 3D which is quite often available prior to a survey for instance in form of blueprints, previously generated 3D models at a lower resolution from other sources or any kind of CAD models. Alternatively scans can be acquired and triangulated in order to receive the required input. This course of action is recommendable as in addition to the geometric description of an object radiometric information is collected in form of intensity values. These values allow to draw conclusions about the achievable precision as described under Section 5.1. Detailed knowledge about an object's shape is also important to estimate potential discretisation errors due to an insufficient local sampling rate. It has to be emphasised that the quality of the object information – for instance the precision of the model or its level of detail – directly correlates to the quality of the planning process. This fact appears to be paradox as the exact shape of an object, which should be described by geodetic observations, has to be known beforehand. As a consequence the execution of the survey campaign would be obsolete.

2.3 Scanner information

Every geodetic device has got unique characteristics and is subject to certain restrictions for instance limitations in reach. Hence, it is crucial to consider such factors during the planning stage. For terrestrial laser scanners model-specific characteristics such as the angular resolution are of particular interest as this information is vital for the simulation of TLS observations. If one is interested in preparing engineering surveys appropriate stochastic information about the elementary observations of a laser scanner, namely directions, tilt angles and distances, has to be known. The combination of simulated laser scanner observations and corresponding stochastic information allows prediction of the theoretical precision of individual points as a function of the chosen viewpoint.

2.4 Type of registration

As for multiple scans the registration between the results of different view point acquisitions is mandatory, the type of registration plays an important role for the optimum viewpoint selection. In principle, too little viewpoints may result in insufficient overlap between scans, while too many scans increase the computational efforts and may cause difficulties to combine all scans with a lot of overlap into one coordinate system. Depending of the type of object, various methods for the registration of different scan worlds exist. The first technique incorporates so-called tie-points or better tie-areas, i. e. common points in two point clouds, and estimates transformation parameters by minimizing some distance between these groups of points /Besl & McKay 1992/, and a lot of subsequent publications. The second technique relies on well-defined targets, which are brought into the scene (planes, spheres, etc.) or already exist in the scene (natural targets, flat surfaces, features, etc.). Additionally, within engineering geodesy the use of separate traverse lines or polygons has proven to be very flexible and advantageous. Each registration technique requires a specific type of connection between viewpoints. Therefore the type of registration, which has to be specified for each project, has to be defined before the optimization process can start.

3 DATA PREPARATION

This Section focuses on simulation of laser scanning observations as a requirement for viewpoint planning. At first point clouds have to be simulated which have been captured from one or several viewpoints. In order to achieve this, the following information has to be defined by the user according to Section 2, namely:

- 3D coordinates of potential viewpoints,
- angular resolution for the simulated scan,
- maximum reach of the simulated scanner,
- triangulated 3D model of the object of interest.

Based on this information ray casting can be conducted from every viewpoint. Therefore a 3D vector field is generated based on the desired resolution of the simulated laser scanner. Subsequently the first intersection points between 3D model and vectors lead to simulated point clouds. An additional scanner parameter that may be used for filtering is the maximum reach that removes points from the simulated point cloud if the distance between instrument and object point lies above the scanner's capability. In this contribution a model of a statue, that is referred to as Gauss in the following, is used to demonstrate ray casting. The input model is a scaled version of a digitised bust of Carl Friedrich Gauss. The model has a width of 3.64 m, a depth of 2.68 m and a height of 5.58 m.

The input data consists of a triangulated 3D model, as depicted in *Fig. 1a*. The yellow sphere denotes the viewpoint from which the TLS is simulated. Before a laser scan observation can be deployed, two tuneable parameters need to be defined namely the region of interest as well as the angular resolution which influences the resulting spatial sampling on the object's surface. In order to define the region of interest, the bounding box of the object is computed as depicted by the yellow semitranslucent box in *Fig. 1b*. Methodically it is not necessary to compute the bounding box, yet it is recommended, as it usually reduces the required computational effort. Based on the bounding box, the horizontal and vertical field of view is defined which is represented in *Fig. 1b* by a red respectively a green surface originating from the viewpoint. Subsequently the ray casting process itself can be conducted which leads to a simulated point cloud as signified by small green spheres on the object's surface depicted in *Fig. 1c*.

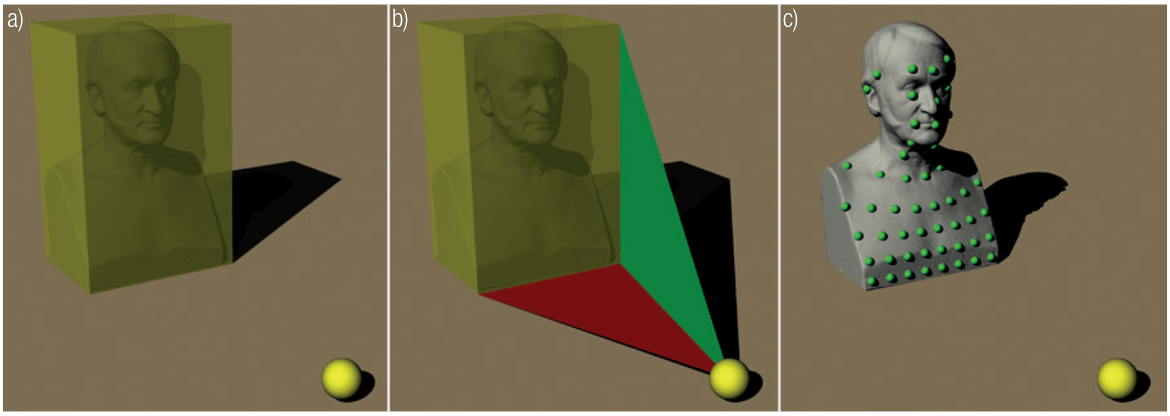

Fig. 1. | a) 3D model and simulated viewpoint (yellow sphere); b) Horizontal (red surface) and vertical field of view (green surface) that encloses the yellow translucent bounding box; c) Simulated TLS points (green spheres on the object's surface)

4 THE SURVEY CONFIGURATION PROBLEM FROM AN ECONOMIC PERSPECTIVE

A prerequisite before carrying out a classical engineering survey based on total station observations is to perform a sophisticated network design or network optimisation, respectively /Niemeier 2008, 331 ff./. The major aim of this task is to receive an optimal solution that satisfies homogeneity of surveyed points in terms of accuracy and reliability, for instance by carefully controlling the redundancy numbers of observations. While these aspects are purely seen from an engineering perspective, an economic point of view is also essential as /Gösseln & Kutterer 2015/ demonstrate on example of a tacheometric network. For this sake a minimisation of the required expenditure of work needs to be undertaken which has to be smaller than a predefined value. This measure can either be defined by economic means or by a client for instance at a construction site where certain other design steps can only be interrupted for a predefined amount of time during the survey. The following equation describes this problem by

$$\sum a_j n_j \leq \sum_A , \tag{1}$$

where a_j denotes the required effort for a single observation while n_j represents the amount of repetitions /Niemeier 2008, p. 335/. A detailed summary on network design is for instance given by /Ghilani 2010, 455 ff./. While Eq. (*1*) is dependent to the required effort for a single observation and its repetitions within the context of total station surveys, this circumstance is now transferred for usage with TLS and follows

$$\sum VP\left(HFOV, Res, Filter\right) \leq \sum_A . \tag{2}$$

This adaption of the original equation had to be made as the time of a single observation with a TLS can be conducted in split seconds. Concerning Eq. (*2*) it can be seen that the expenditure of work is a function of the required number of viewpoints *VP* as well as the current settings of the scanner and should be as large respectively smaller than the maximum expenditure of work $\sum_A$. It has to be emphasised that the amount of viewpoints *VP* should be minimal due to the fact that changing the scanner's position is the most time consuming part in comparison to the mentioned scanner settings. The settings of the scanner include the horizontal field of view *HFOV*, the chosen resolution *Res* and eventually the filter frequency *Filter* where distance measurements can be repeated respectively filtered multiple times.

In summary these settings influence the acquisition time carried out from one particular viewpoint. The horizontal field of view has been chosen in this context as it substantially influences the time of acquisition due to the fact that the revolution of the scan head around the rotation axis is significantly slower than the one of the deflection mirror. *Tab. 1* gathers exemplarily the scanner performance of a Z+F Imager 5006 h /Zoller & Fröhlich 2010/ in dependence to various scanner settings. The outer left column gathers several settings of the scanner that influences the angular increment (see second column from the left). The remaining columns contain information on different noise settings of the distance measurement unit. Each cell contains the according scan duration for a panorama scan. A comparative look at different scan settings reveals a large span of scan durations which hence directly influences the expenditure of work. As a consequence a setting has to be chosen by the user that requires the shortest length of stay on one viewpoint where the resolution is still sufficient not to cause unacceptable sampling errors.

As laser scanners can only acquire information within their line of sight, several viewpoints are required in order to fully capture the surface of a closed 3D object. Hence, a possible small combination of viewpoints is of interest that covers as much as possible of an object's surface. The issue that has to be solved for identification of optimal viewpoint sets is referred to as set cover and belongs to the so called NP-completeness problems as defined by /Karp 1972/. This type of viewpoint planning can be used to estimate how long it would approximately take to capture a scene in the field, which is vital for the preparation of field trips, expeditions or other survey campaigns. It also helps to check if a region of interest has been sufficiently acquired.

A pictorial interpretation of this visibility problem has been introduced by /Chvatal 1975/ as the art gallery problem. It is assumed that an art gallery has to be observed by a minimum number of guards. The geometry of the gallery is described by a simple polygon that is represented by black lines in *Fig. 2*. Guards are depicted by coloured circles while their visibility polygons are tinted in the same colour. Regions which can be observed by more than one guard are tinted in grey. Dotted lines signify boundaries of a viewpoint's visibility field. In this example the whole gallery is controlled by four guards. As this circumstance can usually not be achieved in practice due to occlusion or restrictions in terms of perspective, compromises have to be made.

In order to solve the stated problem, a set of potential viewpoints has to be predefined by the user as it is not possible to determine an analytic solution. Therefore a deterministic strategy has to be chosen where a grid or another different systematic distribution, that restricts the computational effort of the solution, defines the solution space. On each grid point ray casting is conducted based on predefined settings of a simulated scanner which yields in simulated point clouds. The area that is covered by a potential viewpoint is referred to as set cover. Afterwards the actual viewpoint planning is initiated while different strategies will be discussed throughout the article.

A possible solution to identify the smallest possible set of viewpoints is the so called greedy algorithm /Chvatal 1979/ who's functionality is described by /Slavik 1996/ as follows "[…] at each step choose the unused set which

Resolution	Angular increment	Sampling at 25 m distance	Low (50 rps)	Normal (25 rps)	High (12.5 rps)
Preview	0.288°	125.7 mm	13 s	25 s	50 s
Middle	0.072°	31.4 mm	50 s	1:41 min.	3:20 min.
High	0.036°	15.7 mm	1:41 min.	3:22 min.	6:44 min.
Super High	0.018°	7.9 mm	3:22 min.	6:44 min.	13:28 min.

Tab. 1 | Scanner performance of a Z+F Imager 5006h in dependence to various scanner settings

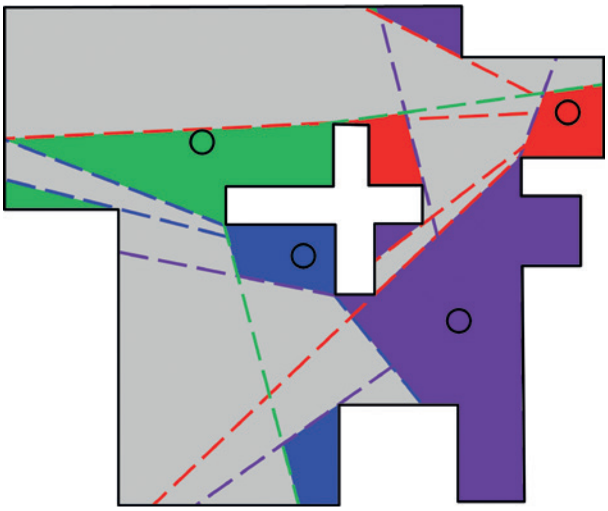

Fig. 2 | An art gallery (black lines) is observed by four guards (circles)

covers the largest number of remaining elements" and "[…] delete(s) these elements from the remaining covering sets and repeat(s) this process until the ground set is covered". This sequential strategy is also referred to as next-best-view method /Scott et al. 2003/ and adds another viewpoint per iteration until a satisfactory solution was found. This course of action bears the drawback of being dependent to the chosen starting point. This means that different solutions arise if the problem is approached from varying starting points.

An algorithm that deploys a greedy algorithm for identification of optimal TLS viewpoints has been proposed by /Soudarissanane et al. 2008/, /Soudarissanane & Lindenbergh 2011/, /Soudarissanane 2016/. A comparable approach has been published by /Ahn & Wohn 2015/. As an input a 2D map is derived from a given 3D model of a scene as "Almost all 3D indoor scene can be reduced to a 2D map by taking a horizontal cross section of the scene at for instance the height of the sensor. This approximation of the 3D surrounding as a 2D map results in less intensive computations" /Soudarissanane & Lindenbergh 2011/. In contrast to Eq. (*2*) that describes the expenditure of work in laser scanning, a minimum number of viewpoints is desired to cover a region of interest. Again a trade-off has to be found that serves both, the number of acquisitions and the required effort for registration. The optimisation problem is tackled by considering three criteria:

- Completeness: All edges of the 2D map should be covered by at least one viewpoint.
- Reach: All edges are captured from at least one viewpoint that is not closer as the minimum distance of a scanner d_{min} and the maximum distance between instrument and edge d_{max}.
- Incidence angle: All edges are acquired from at least one viewpoint where the according incidence angles fall below a maximum threshold α as this influence causes the largest falsifying impact according to /Soudarissanane et al. 2011/.

The left part of *Fig. 3* depicts an example of a visibility polygon for a complex room. The outer bound polygon $\mathbf{P}_0$ is outlined by red lines. Interior obstruction polygons $\mathbf{P}_{hj}$ ($j = 1, \ldots, 6$) are represented by blue areas. The interior of these polygons are not visible. A simulated viewpoint **O** is depicted by a red star. The visibility polygon **V** from this location **O** is represented by the green area. On the right a simulation of nineteen viewpoints is shown that are required to cover all the edges under range and incidence angles constraints. The resulting visibility polygons are represented by grey areas.

While 2D maps may be a –suitable simplification for indoor scenarios, they are definitely inappropriate to describe complex structures or natural scenarios. As a consequence /Ososinski & Labrosse 2014/ introduced a planning strategy where spatial data is used in form of point clouds. Low resolution or decimated scans serve as input for the planning algorithm. Since ray casting cannot be carried out based on point-wise data an alternative representation is created by usage of spatial indices. In this case an octree /Meagher 1982/ is generated where all occupied cells assemble a simplified version of the original dataset. An octree of the dataset depicted in *Fig. 1* can be seen on the left in *Fig. 4*.

The ray casting process is only carried out for the corners of all cubes individually. As an outcome three states can be distinguished that are depicted in the centre of *Fig. 4* – a face of a cube is fully visible (green), partially visible (blue) or not visible (red) from a given viewpoint (yellow sphere). Based on an assessment scheme every viewpoint receives an individual score that considers the

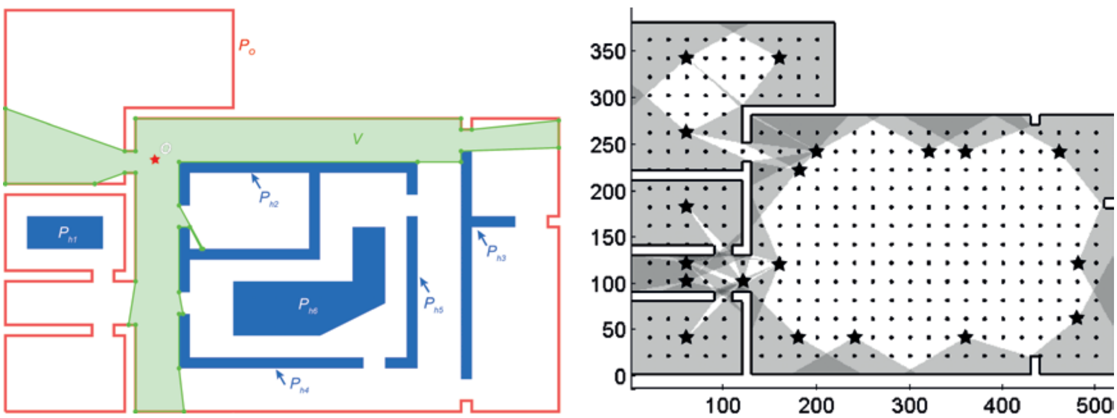

Fig. 3 | The left part of the figure depicts an example for a visibility polygon based on a 2D map. On the right nineteen optimal viewpoints are represented by stars (both figures by /Soudarissanane & Lindenbergh 2011/)

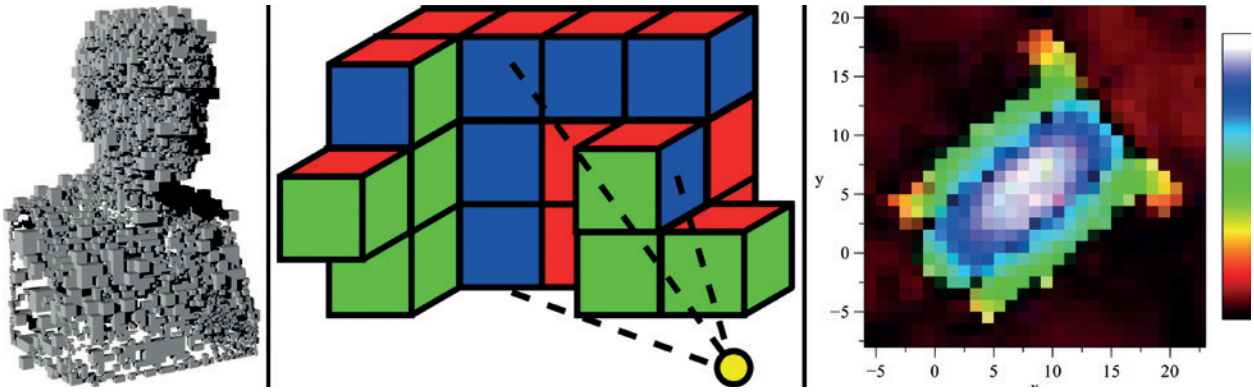

Fig. 4 | Octree representation of the dataset depicted in Fig. 1. Example for face visibility from the yellow viewpoint (centre) and heat map (right) of potential viewpoints. Both figures by /Ososinski & Labrosse 2014/

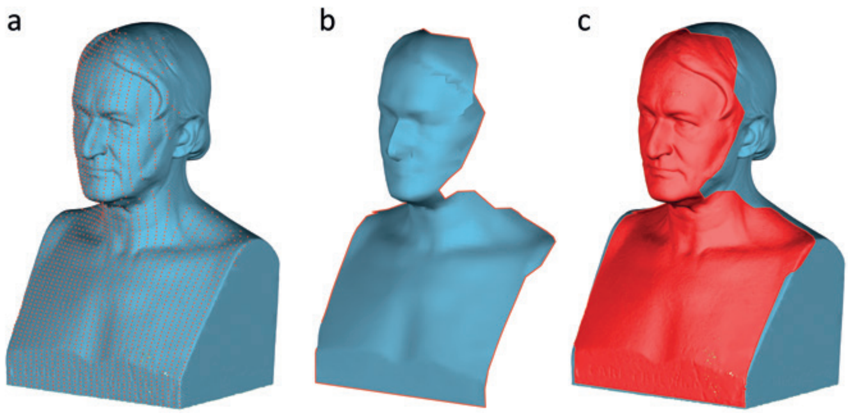

Fig. 5 | Simulated point cloud (red dots) on the model's surface (a), triangulated point cloud with outer boundary (b) and projection of the boundary onto the object of interest (c)

aforementioned visibility check, angle of incidence and distance to an octree cell. For the determination of an optimal set of viewpoints, a greedy strategy is conducted. This sequential strategy selects the viewpoint with the highest score and deletes the corresponding octree cells from the original dataset. Then all remaining viewpoints receive new scores while the strongest one is again selected. This procedure is repeated until no octree cells are remaining. *Fig. 4* illustrates a heat map on the right that visualises the scores of individual viewpoints.

Despite the fact that /Ososinski & Labrosse 2014/ apply 3D information as an input and check for completeness of the resulting viewpoint plan, the issue of registration is not considered. In addition, the description of a point cloud by an octree only describes an approximation of the original geometry. A contribution that addresses registration and works on the full resolution of the given 3D model has been proposed by /Wujanz & Neitzel 2016/. A meshed 3D model serves as input of the procedure. After definition of potential viewpoints, ray casting is conducted from all sensor positions. A simulated point cloud is depicted in *Fig. 5a*. Then the point clouds are triangulated, as illustrated in *Fig. 5b*, while the outer boundary is projected onto the original model in *Fig. 5c*. By this, a common geometric description has been achieved that is used to compute overlap by identifying identical triangles within different datasets. The determination of optimal viewpoint sets is tackled in a combinatory fashion.

The reason why a combinatory strategy was chosen can be explained by a comparison to adjustment calculus. In parameter estimation one tries to find the global minimum which is only possible if the entire solution space is considered – this corresponds to combinatory methods. Greedy strategies match the case where the solution most likely forms a local minimum. By introduction of a required relative overlap among point clouds, only solutions are considered that can be registered to a common dataset. This is achieved by assembling adjacency matrices from the field of topology /Linkwitz 1999/. An extension of the approach also considers if the overlapping region between two point clouds provides sufficient geometric information for surface based registration.

5 ON VIEWPOINT PLANNING IN THE CONTEXT OF ENGINEERING GEODESY

Up to now, economic aspects related to viewpoint planning have been discussed. But when considering the viewpoint planning or data acquisition, respectively, in the context of engineering geodesy, the accuracy of the laser scan and the derived products should also be accounted for. Hence, in the context of engineering geodesy, the determination of a viewpoint does not only impact economic aspects but also the achievable accuracy. This will be explained in more detail in the following.

5.1 Influence of a Viewpoint onto Achievable Accuracy and Completeness

For the sake of engineering geodesy every survey campaign requires thorough viewpoint planning in order to ensure a required precision of the measurements. For this, detailed knowledge about a sensor's stochastic characteristics is of vital importance as it allows to predict the achievable precision of individual points in relation to a chosen survey configuration. The most critical component in this context is the reflectorless distance measurement unit, a key technology that finally lead to the development of TLS. Several influences onto the precision of reflectorless distance measurements are known, for instance:

- the object distance /Elkhracby & Niemeier 2006/,
- surface properties /Zámečníková et al. 2014/,
- varying incidence angles /Soudarissanane et al. 2008/, /Zámečníková & Neuner 2014/.

Even though vast research efforts have been spent on the subject, no coherent theory emerged that allows considering all potential influences. Interested readers are referred to /Soudarissanane 2016/ for a sound summary on this very demanding topic. As a consequence no contributions on viewpoint planning that allowed the prediction of precision were made.

A novel way to model the stochastic behaviour of TLS was introduced by /Wujanz 2016/ as a first proof of concept. The same method has then been refined and applied for the sake viewpoint planning for engineering geodesy /Wujanz et al. 2016/. In general, the idea is to use the originally recorded signal strength respectively the intensity to draw conclusions on the noise level of distance measurements. In other words one can say that the stronger the reflected signal the more precise the distance measurement and vice versa, which is a well-known fact in signal processing. *Fig. 6* illustrates a flow chart of the procedure. On the very left an intensity coloured point cloud is depicted that serves as input. For every point the intensity is used to estimate the precision of the distance measurement σ_{Dist}. Therefore the mentioned stochastic model is required that is depicted in the centre of the figure. This information is then combined with the precision of the applied angle encoder by means of variance-covariance propagation (VCP) that leads to the spatial precision σ_{3D} of the point. The application of the procedure to all points results in a "stochastic" point cloud as illustrated on the right and describes the fundament for viewpoint planning.

It is obvious that the required model of the object of interest has to contain radiometric information. If this is not the case assumptions have to be made for instance by defining a constant quotient of reflection for the entire object. Subsequently several potential viewpoints need to be defined from where the object may be observed followed by a simulation of respective laser scans. Then the signal deterioration is computed /Höfle & Pfeifer 2007/ that is provoked by a certain survey configuration. A relative loss of signal causes a decrease in precision. After assigning stochastic properties to all points from all simulated viewpoints the actual selection of an optimal viewpoint is made. Therefore all points which have been observed from one viewpoint are filtered according to their spatial precision in dependence to the required precision. Subsequently the relation between extend of remaining points and the entire model surface area is computed. Thus, this measure can be interpreted as a measure of completeness in regard to the region of interest.

If the level of completeness is too low then a viewpoint is regarded as uneconomic and cannot be the optimal solution. The optimal viewpoint fulfils the required level of completeness and features the lowest average of spatial precision based on all filtered points. *Fig. 7* depicts the model of interest on the left where constant radiometric properties are assumed. Spheres represent potential viewpoints. In the right half of the figure the mean spatial precision of all potential viewpoints is colour coded. The best results appear to be the closest three viewpoints to the object. As their level of completeness lies below a predefined threshold neither of them represents the optimal solution (as highlighted by pink hemispheres). As a consequence the dark green sphere signifies the optimal viewpoint for acquisition of the object of interest.

5.2 Impact of a Viewpoint on Parameter Estimation

Laser scans are used for area-based analyses in most times. Hence, not the individual point is of interest but the aggregation of points sampling an object, which leads to the examination of a surface. After data acquisition, this surface is parameterized in some way to

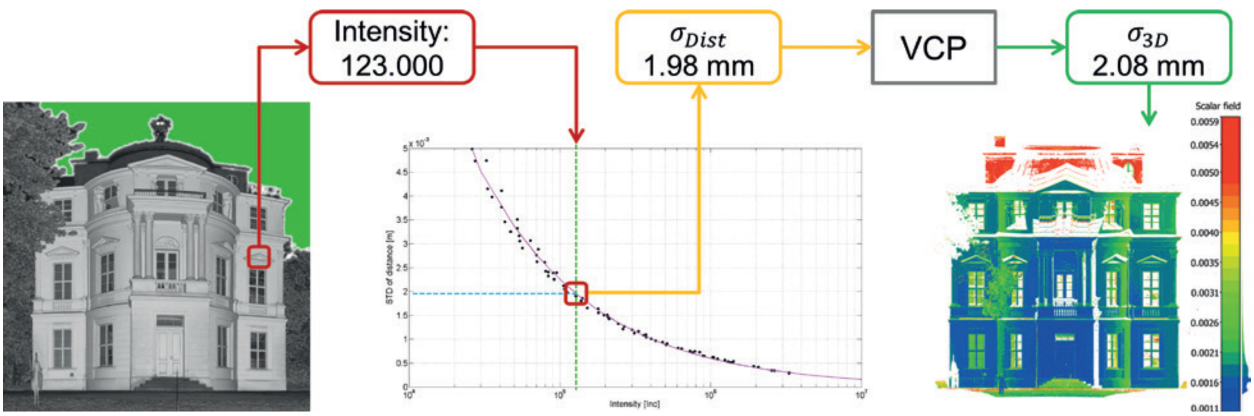

Fig. 6 | Flow chart of the process that computes the spatial precision of individual points

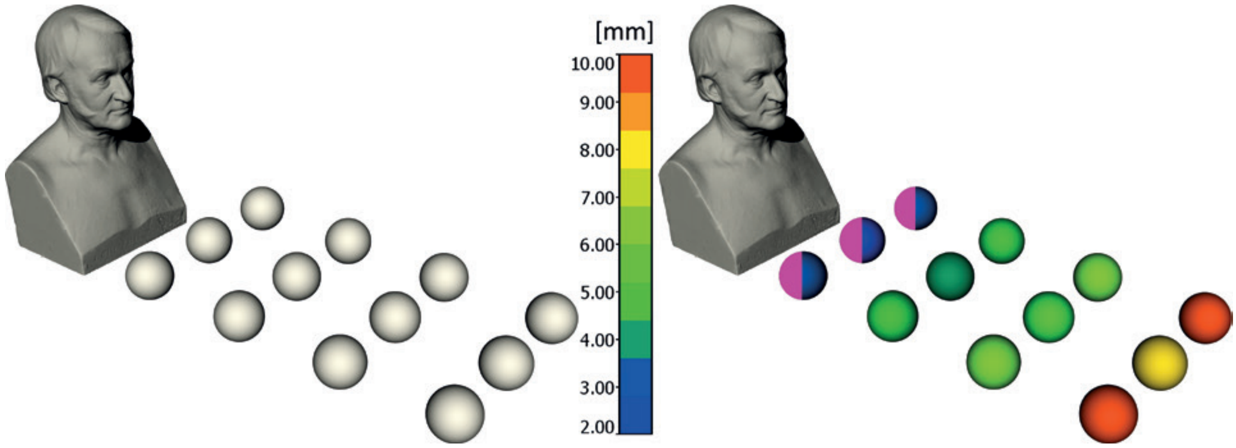

Fig. 7 | Model of interest and potential viewpoints (left) and result of viewpoint planning (right)

gain the wanted area-based parameters. E. g., a main reflector of a radio telescope is parameterized by a rotational paraboloid /Holst et al. 2015/, a dam by local planes /Eling 2009/, a cooling tower by a hyperboloid /Ioannidis et al. 2006/, a tunnel by a cylinder /van Gosliga et al. 2006/ and a television tower by several planar circles /Schneider 2006/. Hence, the sampled surface is parameterized and approximated in all of these analyses by estimating the corresponding surface parameters.

At this approximation, the number of observations is usually sufficient regarding redundancy to estimate the surface parameters. The large number of scan points implies high accuracy and reliability of the derived results. However, both accuracy and reliability rather depend also on the regularity of the object sampling. At laser scanning, this object sampling is irregular due to the polar deflection. As a consequence /Holst 2015/ and /Holst & Kuhlmann 2014a/ show that the variation of the partial redundancies is a better indicator – compared to the absolute redundancy – for certifying the quality of the results of the surface approximation. These partial redundancies combine the functional model, the stochastic model and the irregular sampling density that is due to the viewpoint. In this analysis /Holst 2015/ reveals the large impact of the viewpoint on the parameter estimation.

Closely connected to the impact of the viewpoint is the fact that the object knowledge is limited in most cases. This means that the scanned object is not known in every detail due to its complex structure or unknown deformations. Either this deformation is not of interest – e. g., if a simple 3D model of a house is build – or the analysis of this deformation is the aim of the scanning – e. g., at the area-based deformation analysis of a radio telescope /Holst et al. 2015/. In both cases the least-squares estimates of the surface parameters will be biased /Holst et al. 2014/. The magnitude of this bias depends on the viewpoint of the laser scanner /Holst 2015/.

The connection between viewpoint of the laser scanner and the limited object knowledge can be explained based on a simulated example /Holst et al. 2014/: the scanning of a partially deformed plane from different viewpoints. *Fig. 8* shows the survey configuration from station no. 1 (black cross) and the resulting total standard deviation of the scan points based on the accuracy level of a Leica HDS 6100. This plane is deformed at four different positions, see *Fig. 9*. These deformations are unknown and the surface is, thus, parameterized as a plane leading to the parameters normal vector and its rectangular distance to the laser scanner station. This plane is not only scanned from station 1 but also from the stations 2–5, shown in *Fig. 9* as a projection on the plane. This variation shall illustrate the dependence between laser scanner station and parameter bias.

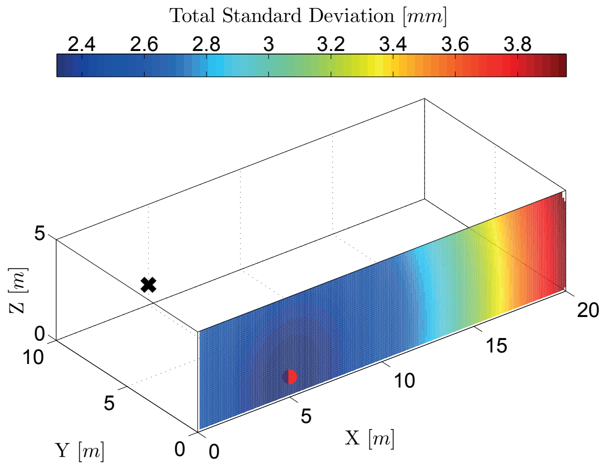

Fig. 8 | Simulated scanning of a deformed plane: survey configuration of viewpoint 1 (black cross = viewpoint, red dot = projection of viewpoint on plane) /Holst et al. 2014/

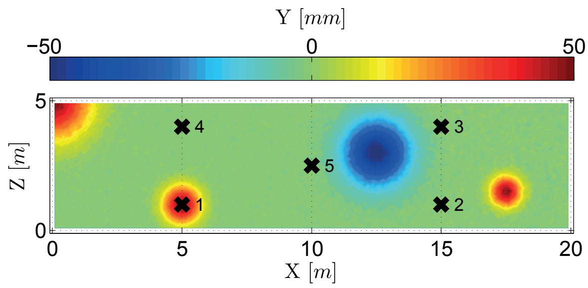

Fig. 9 | Simulated scanning of a deformed plane: unknown deformations and projections of different viewpoints on plane (black crosses) /Holst et al. 2014/

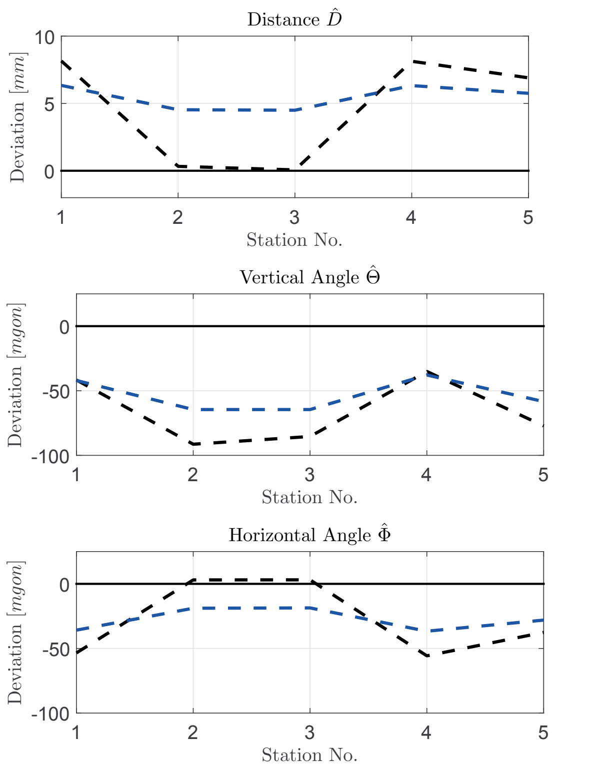

Fig. 10 | Simulated scanning of a deformed plane: biases of the parameter estimates depending on different laser scanner stations (black = original point cloud, blue = reduced point cloud) /Holst et al. 2014/

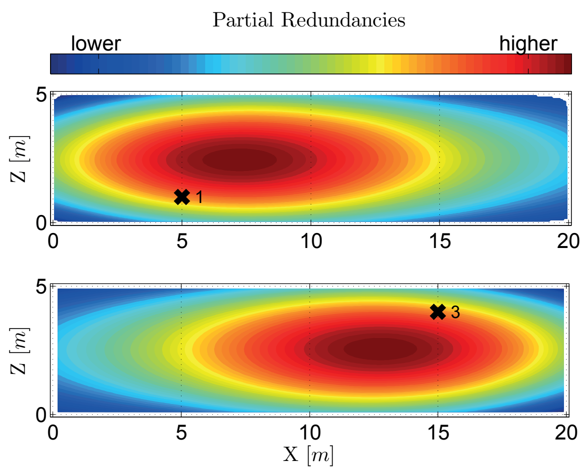

Fig. 11 | Simulated scanning of a deformed plane: partial redundancies at viewpoint 1 (top) and viewpoint 3 (bottom) /Holst et al. 2014/

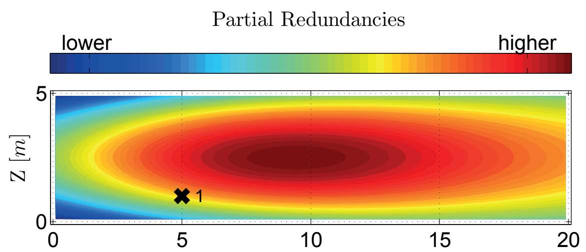

Fig. 12 | Simulated scanning of a deformed plane: partial redundancies at viewpoint 1 after point cloud reduction /Holst et al. 2014/

The results of the parameter estimation are shown in *Fig. 10* for each laser scanner viewpoint. For better readability, the estimated normal vectors are transformed to the horizontal angle and the vertical angle of the plane. Furthermore, the parameters are shown as deviations to the true ones to highlight the varying biases. As it can be seen, the biases indeed vary between the different viewpoints. Hence, the viewpoint of the laser scanner significantly impacts the parameter estimation.

The reason can be found by analyzing *Fig. 11*: the partial redundancies significantly depend on the viewpoint of the laser scanner. Since these partial redundancies can also be interpreted as a weight for each scan point, the unknown deformations shown in *Fig. 9* are also weighted differently between the laser scanner stations. Consequently the parameter estimates also depend on the viewpoint of the laser scanner.

A strategy for reducing this bias is the point cloud reduction to a regular grid of observations, see *Fig. 10*. This leads to a distribution of the partial redundancies whose dependence on the viewpoint is reduced, see *Fig. 12*. This can be seen by the fact that the position of maximal partial redundancies shifts to the center of the plane in contrast to the previous situation shown in *Fig. 12*.

In summary, this example highlights the impact of the viewpoint at laser scanning on the parameter estimation which is due to two reasons: the sampling density is irregular and the object knowledge is incomplete. While this example only considers a scanned plane, /Holst et al. 2014/, /Holst & Kuhlmann 2014a, 2014b/, /Holst et al. /2015/ also investigate these biases for different kinds of deformation analyses. In principle, a reduction of this bias and its variation that depend on the viewpoint can be obtained
(1) by thinning the point cloud to a regular sampling (as shown above),
(2) by inserting spatial correlations between neighboring points or
(3) by robust estimation /Holst et al. 2014/.
However, each of these solutions bears disadvantages since (1) scan points are eliminated, (2) nearly completely filled covariance matrices need to be processed or (3) different kind of error models are used for approximation.

5.3 Detectability of Deformations in Dependence of the Survey Configuration

The parameters influencing the economic aspects of geodetic data acquisition by laser scanning mentioned in Eq. (*2*) as *HFOV*, *Res* and *Filter* as well as the geometric relation between the scanned object and the scanner site abbreviated *Geom* influence the accuracy of the (parametrised) scanned object as well as the possibility to detect deformations of the object. The latter is called sensitivity analysis in the engineering geodetic context /Niemeier 1985/. In general any method to estimate the influence of different input quantities on output quantities is called sensitivity analysis. If the result of this analysis should not depend on local properties, like in linearized least-square adjustment, sample based methods or with other words Monte Carlo Simulations are preferred tools /Saltelli et al. 2000/, /Schwieger 2005/.

If non-linear relationships between input and output quantities are existent, the recommended method is the so-called variance-based sensitivity analysis. The measures reflecting the influences are e.g. so-called Sobols total indices. They indicate the relative importance of the input quantities with respect to the output. In connection with the variance analysis an optimization of the influence factors may be realized. /Schwieger 2007/ has adapted the method for the analysis of a kinematic Kalman Filter for vehicle positioning. Here the importance of the different sensor data with respect to the different state variables like position or velocity were analysed and the variance was improved with the help of the variance based sensitivity analysis. /Tiede 2005/ optimised the configuration of a geodetic network for volcano monitoring.

In the case of terrestrial laser scanning the output may be the average standard deviation of the scanned object or the standard deviation of a parameter describing a surface or at a chosen point on the object. The input quantities would be the one mentioned before. The variances for each output quantity may be generally calculated as a function of the input variables

$$\sigma_i = f(HFOV, Res, Filter, Geom), \; i = 1, \ldots, u, \tag{3}$$

with u being the number of output variables. The respective sensitivity measures, Sobol's total indices, are determined by

$$S_{ij}^{sob} = \frac{\sigma^2_{x_i/\sigma_j}}{\sigma^2_{ij}}, \; i = 1, \ldots, u \text{ and } j = 1, \ldots, n, \tag{4}$$

with n being the number of influencing parameters, here four parameters are mentioned and with $\sigma^2_{x_i/\sigma_j}$ as the conditional variance including all influences in non-linear models caused by the input x_i on the output. For the computation of the variance and the conditional variance by sampling based models the authors refer to /Saltelli et al. 2004/, /Schwieger 2005/. Eq. (*3*) gives an impression if a given accuracy threshold is reached and if this is not the case Eq. (*4*) will provide information which of the input quantities have to be improved to get the largest gain for the output accuracy; that is the one with the largest value of S_{ij}^{sob}.

Besides, the sensitivity of the viewpoint with respect to an assumed deformation model may be the aim of an optimisation; meaning the minimal detectable deformations should be optimized. In this specific application the terms sensitivity analysis in the engineering geodetic and general sense will be joined. The accurate estimation of given deformations may be the aim (output or left hand of Eq. (*4*)) or e.g. the determination of parameters of a surface modelled for instance by B-splines, e.g. the number of the respective control points, may be the optimisation aim /Harmening et al. 2016/. In principle the variance-based sensitivity analysis can be used to support the viewpoint planning in the context of engineering geodesy.

6 CONCLUSIONS AND OUTLOOK

This article featured an introduction into the subject of viewpoint planning while outlining the necessity of performing this task at the very beginning. In order to solve the configuration problems in the context of TLS several questions and restrictions need to be predefined. The minimum input for viewpoint planning is information on an object's shape either in 2D or in 3D as well as some specifications on the scanner that should be simulated. A vital step, before the actual optimisation process can be carried out, is described by the simulation of TLS observations from predefined viewpoints. Several ways of how to determine minimum viewpoint sets have been discussed that revealed large methodical differences both in the input data and the definition of what an optimal solution is. Various methods that can be associated to planning of engineering surveys demonstrated the influence of a chosen viewpoint onto the achievable precision of individual points, its impact on parameter estimation as well as the detectability of potential deformations.

This relatively young field of research just started to scratch on the surface of various problems so that no practicable solution is available on the market. Furthermore all presented solutions focus on particular aspects of the survey configuration while future works should allow of combining various methods in order to precisely receive desired results. Other prospective issues can be associated to estimating of how and how precise point clouds can be registered into one common coordinate frame. Furthermore the question arises how optimal viewpoints can be transferred into the object space.

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