

STRUCTURAL MONITORING OF TUNNELS USING TERRESTRIAL LASER SCANNING

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ABSTRACT

In recent years terrestrial laser scanning is rapidly evolving as a surveying technique for the monitoring of engineering objects like roof constructions, mines, dams, viaducts and tunnels. The advantage of laser scanning above traditional surveying methods is that it allows for the rapid acquisition of millions of scan points representing the whole surface of the object considered. Still it is a big challenge to obtain accuracies and precisions in the millimeter level when quantifying deformation of an object between epochs. In this work two main steps are distinguished that together strongly contribute in obtaining results close to the signal to noise ratio of scanners. The first step aims at obtaining for each epoch a point cloud of optimal quality. The second step consists of an adjustment and testing procedure that identifies deformation while taking into account both data redundancy and individual point quality. The discussion of both steps is illustrated using several examples from mainly tunnel monitoring projects in the Rotterdam area.

1. INTRODUCTION

A terrestrial laser scanner samples its 3D surroundings by determining the range distance from the scanner to its environment at regular horizontal and vertical angle intervals, (Shan and Toth, 2008). Modern scanners are able to obtain within half an hour a representation of their surroundings consisting of millions of points. The ease of use of scanners and their relative portability, that allow transport in the back of a car, resulted in recent years in a rapid increase of popularity. For scans within a range distance of 100 m, typical values for the accuracy and precision of individual scan points are in the order of a few millimeters. Unfortunately several processing steps are needed that lead from one individual scan to a useful end product, like a 3D model of a monument or an industrial installation. As a consequence, it is far from trivial to obtain an end product with a quality in the order of millimeters as well. Here we do not even consider the representation of a static situation, but aim at detecting and quantifying deformation on engineering objects through time.

Well established point surveying techniques using total station, tacheometry or RTK GPS measure the xyz coordinates of an apparent reference point or benchmark, (Gilani and Wolf, 2008). After aligning the measurements in a common coordinate frame, possible displacements of the reference point through time can be assessed. In general, this

procedure is not applicable for terrestrial laser scan data: the individual laser pulses of repeated scans will not hit exactly the same locations. In order to detect deformation between epochs several choices exist: first, the position of apparent reference points can be reconstructed from a registered point cloud. For this purpose, targets can be used that are clearly visible in the scans, or points can be reconstructed on the intersection of structural elements like walls or iron bars, (Rönholm et al., 2006). If the point clouds from different epochs are properly registered in a common coordinate frame, this method allows assessing deformation in all three xyz coordinate directions. Second, in some cases it is possible to identify corresponding objects in a time series of point clouds and parameterize their motion through time, e.g. (Pieraccini et al., 2006). Finally, deformation can be considered in the direction perpendicular to the object surface by creating for each epoch a virtual grid or profiles on the objects surface. In this case preprocessing steps should assure that virtual grid points/profiles from different epochs are indeed comparable.

In this paper we will mainly focus on the last method as this is the most promising for assessing stress related deformation on construction works. The main benefit of terrestrial laser scanning above other structural surveying techniques is the large redundancy in observations that potentially allow detecting deformations well below the nominal individual point quality, (Gordon and Lichti, 2007). In order to optimally benefit from this data redundancy, two steps are essential. First it should be assured that everywhere on the surface of the object of interest enough scan points with a known and sufficient quality are available. This step, discussed in detail in Section 2, considers the measurement setup, the parameters influencing the quality of individual scan points and the influence of standard processing steps like registration and segmentation. Second a method, discussed and illustrated in Section 3, should be used that allows to encode the individual data quality and enables to profit from the given data redundancy.

The complete work flow is illustrated on a series of experiments with laser scanning conducted on notably several tunnel objects in the region of Rotterdam. In the first experiment, (Lindenbergh et al., 2005), scans from an approximately rectangular tunnel of one single epoch were considered. It is explained how the point density depends on the range and incidence angle, and it is demonstrated that laser scanning is suitable to detect deviations in the order of millimeters in an apparent planar ceiling. In (Gosliga et al., 2006) it is described how artificial deformations of a cylindrical tunnel wall in the order of 1-2 cm are detected using a statistical adjusting and testing procedure. In this paper some preliminary results are shown of an ongoing analysis of possibly real deformation in the Rotterdam CS metro station, as sampled by terrestrial laser scanner at three different moments.

2. HANDLING A MONITORING PROJECT

The first step of a monitoring project based on terrestrial laser scanning consists of obtaining a registered point cloud for each epoch considered. In designing the measurement setup, all planned following processing steps should already be taken into account.

2.1 Scanning Geometry

It should be assured that every part of the scene of interest is sampled in each epoch by enough scan points of enough quality. It is obvious that shadowing effects should be taken into account when determining the scan locations to avoid occlusions in the final point

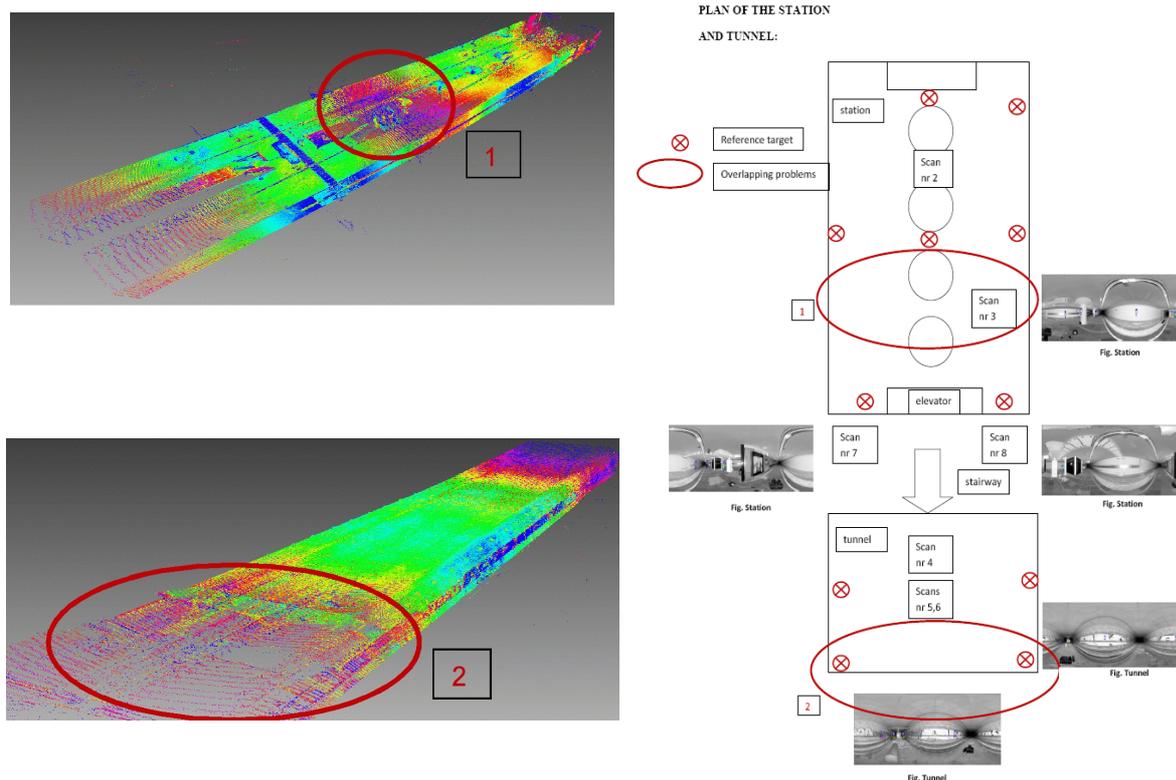


Fig.1. Influence of measurement setup on scan quality. Low point densities and low intensities due to large scan angles can be observed in areas 1 and 2.

cloud. It is advisable to be more critical however. In Fig. 1, left, a registered point cloud in two parts of a metro station is shown, colored by intensity. Blue and green points represent points of relative high intensity, low intensity points are purple. On the right a plan of the station is shown indicating the scan location used to obtain the point clouds on the left. In the plan and in the point clouds two regions are marked by ellipses. Within these regions it is observed that the point density is low but also that the intensity of the points that are available is low as well. Especially in elongated objects like tunnels, the incidence angle increases rapidly with increasing distance to the scanner, (Lindenbergh et al., 2005). The incidence angle is the angle between the incoming laser beam and the surface normal. For a fixed range and fixed surface properties, an increase in incidence angle implies that the pulse returning from the object surface is widened, which implies again that the intensity is decreased and the noise level increased. Moreover, for fixed incidence angle and object surface, also an increase in range will result in noisier scan points. It is concluded that large incidence angles (i.e. above 60 degrees) and long scan ranges (depending on the specifications of the scanner) should be avoided in order to obtain a sufficient point cloud quality, (Soudarissanane et al., 2008). On the other hand, it should also be avoided to plan abundant scans or of a higher resolution than necessary to identify the expected deformation.

Given a CAD model of the scene of interest, or alternatively, a few fast low resolution scans, it is in principle possible to mathematically optimize the scan locations fulfilling boundary conditions that identify the amount and quality of scan points per meter squared. What is still required before such automatic measurement setup design can be performed, is a full characterization of the variance of individual scan points, as it depends

on scanner calibration, scanning geometry, surface properties and environmental conditions (humidity, temperature).

2.2 Registration

For each epoch, the individual scans should be aligned in a common coordinate system, either using scan points representing stable objects in overlapping areas of the different scans, e.g. (Grün, A. and Akca, D., 2005), or using ground control points, like spherical or planar targets. The advantage of using tie points is that the same points can be measured by e.g. a total station, which allows additional validation or connection to a global reference frame. The danger of using a necessarily limited number of control points is that a small bias in positioning the control points with the scanner will propagate into all consecutive processing steps, (Alba et al., 2008; Pesci and Teza, 2008).

Inevitably any point cloud registration will result in some closing errors. Registration software typically reports on the errors it finds at either the control points or at the points representing the stable objects used for registration. In case features as appearing in the scans are used for registration, it should be kept in mind that the registration may be dominated by features that are sampled at a large point density. These are typically features that are relative close to the scanner. When registering elongated scans using a rigid body transformation, the closing errors for points far away from the scanner will be relatively large. Therefore it is advisable to try to visualize and consecutively quantify the closing errors between the different scans in a point cloud.

2.3 Object and Surface Changes

Before an actual deformation analysis is performed, aiming at identifying deformations close or below the nominal scan accuracy, first a quick and preferably automatic change detection should be done, identifying both object and surface changes. In Fig. 2 point clouds colored by intensity are shown as obtained in two different epochs. It is visible in the top right image that in the second epoch a small bench appeared. As a consequence, segmentation into homogeneous and possibly identifiable object parts will have different results in epoch I as in epoch II. Change detection methods developed for detecting such larger changes are described in e.g. (Girardeau-Montaut et al, 2005) and (Zeibak and Filin, 2007).

In Fig. 2, bottom left, a large graffiti tag is visible in epoch I that apparently has been removed in epoch II, Fig. 2, bottom right. To identify such surface changes is important: surface properties directly affect the individual scan point quality. Especially reflective materials, as the silver paint in the graffiti tag, are known to cause biases in the range determination, (Pescia and Teza, 2008).

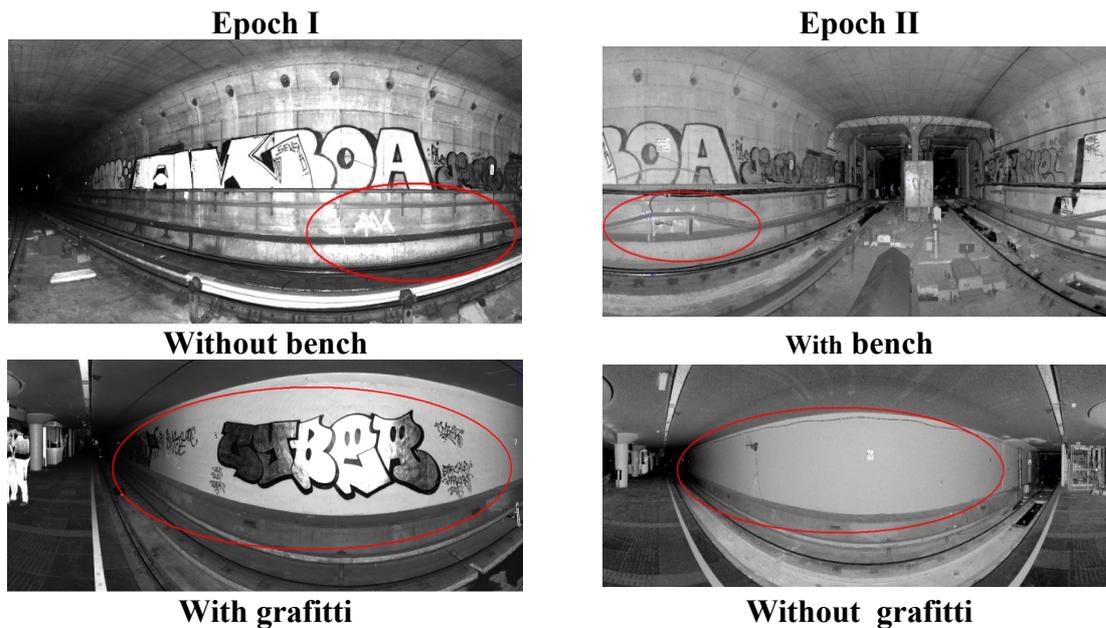


Fig. 2. Object and surface changes, visible in laser scan data colored by intensity.

2.4 Segmentation

In most cases it is a good idea to segment the resulting point clouds of each epoch, using e.g (Gorte, 2007). Segmentation is applied to identify object parts and to establish correspondences between the same object parts in different epochs. Additionally, segmentation is useful to avoid unwanted edge effects: near sharp corners in the point clouds of different epochs, small registration errors may result in locally large (artificial) differences. By first segmenting and second cutting away a sufficient boundary along the edges of the segments, edge effects can be largely avoided.

3. POINT WISE DEFORMATION ANALYSIS

A key ingredient of the developed work flow is the Delft method of adjusting and testing (Teunissen, 2000a and 2000b). By properly modeling the quality of individual scan points and by incorporating the correlation between nearby points potentially deformations well below the single point coordinate precision can be detected. Note that here only deformation perpendicular to the object surface is considered.

This methodology is illustrated on a deformation analysis experiment conducted in the 2nd Heineoordtunnel, (Van Gosliga, 2006). An approximately cylindrical tunnel was scanned two times using the HDS4500 phase scanner. After the first epoch, artificial deformations were place, Fig. 3, bottom, consisting of several small lids, some plates and some boards, all less than 2 cm thick, before the tunnel was scanned again. It should be noted that the methodology to be described next was implemented using only 1 % of the data. This illustrates on one hand that time can be gained by carefully designing the measurement setup, to avoid copious data sets, on the other hand, that detecting smaller deformations is feasible.

3.1 Gridding

In the ideal situation a quality description is given for each individual point $p = (p_x, p_y, p_z)$ in the point clouds of the different epochs in the form of a variance-covariance matrix Q_p , describing realistic variances of the three point coordinates and their relative covariances. In practice, this information is mostly not available. In the case of Fig. 3 a global st.dev value of $\sigma_R = 7.6$ mm was adapted, approximately describing the average standard deviation of the scan points in the deformation direction.

Assume that the object surface is locally parameterized. Such parameterization can be obtained by fitting a model representing the object surface to the point cloud. In Fig. 3 this is achieved by fitting a mathematical cylinder to the complete point cloud of each epoch, representing a cylindrical tunnel as a whole. Alternatively, compare for example (Lindenbergh and Pfeifer, 2005), the point cloud of each epoch is segmented first. Next, any segment having a shape resembling a mathematical primitive like plane, sphere or cylinders can be modeled accordingly. Note as a side step that the parameters obtained from the shape fitting can be used to assess the stability of the scanned objects through time.

With respect to the object surface we may assume that the point cloud points of each epoch are in the form (p_x, p_y, p_R) , where (p_x, p_y) describes the location of the point on the surface. p_R is the remaining coordinate in the direction of the possible deformation, assumed to be perpendicular to the object surface. To suppress the effect of noise and to optimally profit from the data redundancy, the object surface is divided into grid cells of suited size. This size should be large enough to contain enough points in each epoch, but should be small enough to represent possible local deviations and deformations from the object surface. In Fig. 3 a grid cell size of 15 cm was chosen. For all of in this case two epochs I and II, all points in corresponding grid cells are used to determine range coordinates (r_I, σ_I) and (r_{II}, σ_{II}) , for the middle of the grid cell. Note that the more, well-spread points with a small deviation of the average range are available in a certain grid cell, the smaller also the variance σ_i^2 , for that epoch, of the resulting grid center, for $i = I, II$.

3.2 Testing

The question can now be posed if the difference between r_I and r_{II} is significant given their variances. If this difference is significant, it is then concluded that deformation is detected, otherwise the difference is more likely to be explainable by random deviations in the scan measurements. This deformation question can be answered by performing a statistical test on a test statistic

$$T_q = e^T Q_y^{-1} e, \quad \text{with } e = \begin{bmatrix} r_I \\ \sigma_I^2 \end{bmatrix} - \begin{bmatrix} r_C \\ \sigma_C^2 \end{bmatrix}, \quad \text{and } Q_y = \begin{bmatrix} \sigma_{r_I}^2 & 0 \\ 0 & \sigma_{r_{II}}^2 \end{bmatrix} \quad (3.1)$$

Here r_C denotes the weighted average of r_I and r_{II} , where the weight is relative to their variances. In the top left image of Fig. 3, the test statistics for each grid cell are shown. Most are gray, indicating low test statistics, but on the bottom right for example, considerable large values can be observed at the location where the plates were placed.

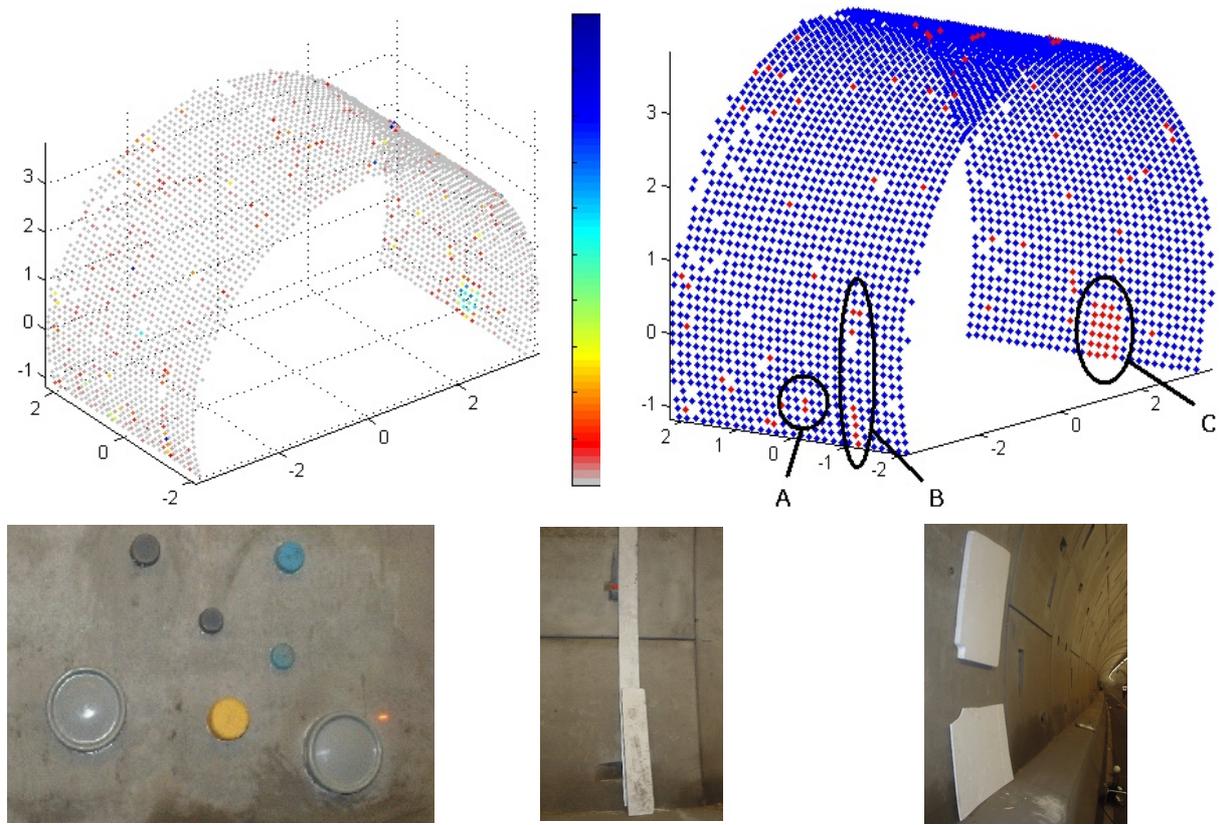


Fig. 3. Bottom: Artificial deformations. A: lids; B: board; C: plates. Top: Test statistics (left); Test results (right): Red grid points are tested as unstable.

The test statistics are evaluated in a stability test, that is, the zero-hypothesis H_0 states stability. Assuming H_0 , the test quantity T_q has chi-square distribution:

$$H_0: T_q \sim \chi^2(q, 0), \quad (3.2)$$

with $q = m - n = 1$ degree of freedom. By m and n , the number of observations, in this case the two ranges, and the number of model parameters, in this case 1 for the common range value, are denoted, resp. Given a reliability level α indicating the percentage of false test decisions that is allowed a critical value κ_α is obtained, which is evaluated against the test statistic. For creating Fig. 3 the reliability level was set at 5 %

In the top right image of Fig. 3 all grid points with a test statistic larger than the critical value are made red and are therefore tested unstable, the other, stable, grid points are colored blue. From the figure it can be concluded that all artificial deformations were found back by the testing method. But also some other grid points were tested as instable. It turned out that these locations coincide with gripper holes in the concrete tunnel plates: small errors in the registration between epochs resulted here in artificial differences. Such errors can be avoided by using a more strict method of segmentation that removes such scan points in small holes.

The benefit of this method becomes clearer when considering smaller differences. Differences above 15 mm were always tested unstable. Most differences below 15 mm were tested stable, but differences starting from 5mm were frequently tested unstable as well. This ‘mixing’ is possible because the number of observations per grid cell is incorporated: larger number of consistent observations will lead to smaller standard deviations per grid cell, which again allows the method to detect smaller deformations.

CONCLUSIONS

In this paper a work flow is described for the use of terrestrial laser scanning for detecting deformation with a size comparable or even well below the individual measurement precision. First point clouds for each epoch are obtained with a preferably high and well-described individual point quality. Using the statistical framework of adjustment and testing theory, realistic variance values of individual points and local data redundancy can be optimally exploited.

Still, many questions remain. First, an a priori characterization of the quality of individual points is under investigation but not yet available. Moreover, most algorithms used for processing steps as registration or segmentation, are not developed to cope with individual variance values and therefore do not yet support proper geodetic error propagation. Only if these results would become available it will be feasible to fully optimize a measurement setup given for example a minimal deformation to be detected and, finally, to fully determine the limits of terrestrial laser scanning in structural monitoring applications.

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