TERRESTRIAL LASER SCANNING FOR DEFORMATION MONITORING

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Abstract: Small scale deformation monitoring using terrestrial laser scanning is gaining considerable attention mainly due to the high spatial resolution of the acquired data. The notion of this paper is to discuss the issues influencing the feasibility of laser scanning for deformation monitoring. Prior to any data collection it is critical to evaluate the scanner's performance within a calibration scheme using independent procedures as well as self-calibration measures depending on the scanner system. The paper discusses methods of surface modelling implemented for deformation monitoring and approaches used to measure the deformation from surfaces. Finally, applications which involve the use of laser scanning in laboratory and non-laboratory conditions are presented to demonstrate the above issues.

1. Introduction

Terrestrial laser scanners have very recently received attention due to the number of measurement benefits including three-dimensional, fast and dense data capture, operation without the mandatory use of targets, and permanent visual record. The growing importance of this technology is also mirrored by the establishment of FIG Taskforce 6.1.5 "Terrestrial Laser Scanning for Deformation Monitoring" and ISPRS Working Group V/3 "Terrestrial Laserscanning". However, the precision of the laser scanners is not perceived adequate for industrial metrology applications, such as deformation monitoring. The notion of this paper is to discuss the issues influencing the feasibility of laser scanning for deformation monitoring and demonstrate this with a number of cases studies.

Initially, in order to ensure the metric integrity of the laser scanner data for deformation analysis, it is critical to independently evaluate the scanner's performance within a calibration scheme, even if the manufacturer has pre-calibrated the instrument. A review on calibration methods for laser scanners is presented in Section 2 considering both independent procedures as well as self-calibration measures depending on the scanner system. It is also discussed that while it is important to perform independent range and angular accuracy evaluations it is also essential to investigate the system performance in terms of self-calibration using raw observables rather than on the basis of Cartesian coordinates.

Considering that the big advantage of laser scanning is that it provides dense 3D information of the surface of an object, Section 3 discusses the effectiveness of deriving best-fitting surface models from which deformations of smaller magnitude than the single-point precision of the scanner can be recovered, instead of detecting deformations in single points. Section 4 presents approaches for the extraction of the deformation. Finally, experimental case studies from laboratory and non-laboratory conditions are presented in Section 5 to demonstrate the above issues. The laboratory case studies refer to the estimation of deformation motion through the use of targets for benchmarking and the precise measurement of a wooden beam and a concrete beam whereby benchmarking is performed through photogrammetry and sensors such as dial gauges. The non-laboratory case study refers to the deformation analysis of a lock and examines the influence of the data collection procedures on the results and how the deformation analysis procedures can provide quality results.

2. Calibration Issues

The metric integrity and performance of an instrument is established through calibration and appropriate statistical control procedures. For this purpose, reference standards with known values for selected points covering the range of interest are measured with the instrument in question in order to establish a functional relationship between the reference and corresponding measurements. The calibration procedure, once established, relies on the instrument continuing to respond in the same way over time. If the system takes unpredictable measurements the calibrated values may not be properly corrected for bias, and depending on the direction of change, the calibration may further degrade the accuracy of the measurements excursion

The millimetre to sub-millimetres accuracies required for deformation monitoring applications using terrestrial laser scanners call for stringent calibration procedures. Test protocols and calibrations are performed using indoor and outdoor facilities. The calibration using indoor facilities would fall under two general categories. In the first category, performance evaluation involves the assessment of the instrument in hardware calibration, distance accuracy and precision, pointing accuracy and precision, laser beam divergence, range and angular resolution, minimum distance between objects that is detectable by the sensor, minimum object size that is detectable by the sensor and stability/degradation of sensor over time. The radiometric aspects, i.e. the evaluation of the observed intensity, may be of less concern for deformation monitoring. Furthermore, the performance evaluation can be carried out using standard artefacts and determining how accurately and precisely the following characteristics can be determined: dimensions, position/location, area/volume, geometry/object identity, etc.

In the second category, performance evaluation involves the assessment of the combination of hardware and software to produce a desired end product. Terrestrial laser scanner data could be used as is (point cloud), but the full potential of such data lies in the use of the data to create 3D models from which positions, dimensions, areas, volumes, etc. can be determined. This process involves software to register multiple scans and to mesh the point cloud, as well as methods to clean/filter and to sub-sample the data. In general, the calibrations obtained from the first category above could be used for propagating instrument errors through to the end product and to determine how to improve the scanner, whereas the calibrations in the second category would be used to measure and explicitly note the performance of the scanner. Metrics to evaluate the scanner performance are harder to establish than the metrics to evaluate the hardware accuracy and precision.

For the hardware calibrations and performance evaluation, many issues have to be resolved. These issues include determining the optical characteristics of the standard targets (colour, reflectivity, texture, etc.), shape, size, material, and placement of the artefacts, and choice of software package. Some hardware-specific issues include developing methods to ensure that the target is perpendicular to the laser and procedures for dealing with instruments that are not setup for single point acquisition.

Most performance evaluation and calibration checks regarding the first category are made on the basis of Cartesian coordinates because this is the immediate result provided to the user. While the measurements of distance and angle are acquired by the instrument in order to calculate the 3D coordinates, these raw values are rarely used to check for possible existence of systematic errors. The majority of authors discuss calibration in terms of a set of independent procedures (use of pre-surveyed signalised targets or comparison with other techniques) and compare differences between coordinates or distances in terms of range repeatability e.g. [1], [2], [3], [4]. Hardware calibration is more difficult to perform because specific facilities are required for such checks. For example, in [5] the calibration procedure is discussed in terms of hardware estimating the eccentricity and axis non-orthogonality errors using dedicated infrastructure such as granite tables and inclinometers.

The evaluation regarding the second category is performed to the surface generation (meshing) algorithms using propagation-of-error e.g. [6]. The first order estimates of error at any point in the mesh are computed as well as second order estimates of spatial covariances between points. The standard correlation measure is the serial autocorrelation. Presence of significant autocorrelation indicates that standard error propagation methods would produce results that are better than warranted, i.e. too optimistic error measures.

Full instrument self-calibration has been investigated only by few authors. In [7] a calibration method and error models for an in-house laser scanner system are proposed using raw observables rather than cartesian coordinates. In [8] the models to correct for significant systematic errors in the observables of the iQsun 880 laser scanner are presented, and additional parameters are estimated that have shown temporal instability. This implies that if further testing confirms the above findings, then some remedial measure is required by the manufacturer to stabilise the instrument. Other self-calibration efforts are reported in [10] and [11].

Clearly, the successful establishment of a terrestrial laser scanner calibration method and the development of test protocols would require the participation, cooperation, and acceptance by the laser scanner manufacturers and end users. For deformation monitoring applications it is even more critical to have standardization of the test protocols, so the results of any deformation study performed by laser scanning would also require the inclusion of testing.

3. Surface reconstruction for deformation analysis

Structural deformation monitoring is typically undertaken using sparse, point-wise observation techniques. Terrestrial laser scanners are attractive acquisition systems in that they provide dense 3D information of the surface of an object. A disadvantage of the technique may be the difficulty to assess some fixed benchmarks on the surface of the deforming area, unless they are special targets that can be recognised by the accompanying software. In contrast to geodetic and photogrammetric monitoring methods where small (but adequately sampled, in the case of digital photogrammetry) targets are desired to minimise pointing error, much larger structured planar targets or 3D shapes (e.g., spheres, cones) are used in terrestrial laser scanning. However, in order to profit in an optimal way from the dense observations, it is favourable to model surface deformation, rather than trying to detect deformation of single points. This section discusses the generation of parametric and implicit surfaces from point clouds.

Deformation analysis requires the reconstruction of surfaces prior to comparing them in different epochs. During surface reconstruction a surface model S' that approximates S is created from a set of sample points P assumed to lie on or near an unknown surface S. A surface reconstruction procedure cannot guarantee the recovering of S exactly, because the information about S is only through a finite set of sample points [9]. Clearly, when the sampling density increases, the surface model S' converges to the original surface S.

In general, surface reconstruction is a complicated problem because the measured points are unorganised and noisy and the surface can be arbitrary, with unknown topological type. Here, "unorganized" means organized only by proximity in the angular domain but not object-wise. Therefore the reconstruction method must infer the correct geometry and features (e.g. a break line or an apex) based on a limited set of sample points. In [9] there is a detailed discussion on the classification of reconstruction methods. However, all reconstruction methods require four basic stages: a) pre-processing in order to eliminate erroneous and noisy data, b) determination of the global properties of the object's surface, which considers possible 'constraints' to preserve special features (like edges), c) generation of the polygonal surface such as triangular or tetrahedral meshes but also parametric surfaces (e.g. low order polynomials over a user-defined reference plane or more general free form surfaces) and implicit surface representations (e.g. for planes, spheres, cylinders, and tori) are used, and finally, d) post-processing of the model to refine and perfect the (polygonal) surface.

Many reconstruction programs perform triangulation, which converts the given set of points into a consistent polygonal model (mesh) [12]. This operation partitions the input data into simplices and usually generates vertices, edges and faces that represent the surface. Triangulation can be performed in 2D (e.g. Delaunay triangulation, triangulated irregular network TIN), 2.5D using DDT (data dependent triangulations [19]) or in 3D, based on local properties of the points defined in 3D.

Many authors report methods implemented for surface modelling of a deforming object that involve simple gridding. In [13] the creation of a regular grid by Delaunay-triangulation is described for the determination of surface deformations of several centimetres observed at the lock gates of a hydropower station during the filling and emptying process.

In [14], [15] it is proposed the use the segmentation method which groups points of similar properties into segments. The method follows the region growing approach for extracting planes. Initially, for each point on the cloud an initial normal vector is estimated by plane fitting. After points with large residuals are excluded, the remaining points are used for the region growing by starting with the initial normal vector and the position of a seed point. With this method the modelling of a tunnel and a lock using laser scanner data has been achieved.

In [16], [17] instead of using surface models to compute an object's surface, the method chosen to model vertical deflections is based on forming analytical models representing the physical bending of a beam. The models are derived from first principles of beam deflection by integration, which essentially yields low order polynomials. Once these models are developed, the coefficients of the polynomials are solved as unknown parameters in a least-squares estimation process. The observations consist of the several hundred 3D point samples from the laser scanner. A single functional model is used to represent the beam deflection but the parameters of the model are estimated for each deflection epoch.

4. Deformation Extraction

The extraction of deformation motion using laser scanner data is usually performed not on single points but on surfaces that have been modeled, as discussed above, and compared in distinct epochs. Single points cannot be used for deformation extraction due to the fact that the same point is not identifiable on multiple scans of the same surface. If the scanner has been maintained at the same position the noise level prevents detection of small deformations.

Direct comparison of benchmark points is discussed in [18] using retro-reflective targets and dedicated algorithms for the accurate determination of their centre. Scans of a deforming object acquired at different epochs were transformed to a common coordinate system. The statistical comparison of vectors along the X, Y, Z directions between each epoch gave deformations less than 0.4mm.

Direct comparison of single points without the use of targets is discussed in [13] where these are located on a uniform grid developed by Delaunay-Triangulation. According to the authors, the grid is identical for the same scans when the scanner has not been moved. Then, for each sampling point, a new value (y`) can be interpolated. The differences of two corresponding y`-coordinates now represent the amount of deformation.

In [15] it is discussed that between two scans of different epoch but with the scanner's position apparently fixed, the comparison of two ranges of scan 1 and 2, $R_p(1), R_p(2)$, allows for deformation extraction as follows,

$$R_p(1) - R_p(2) = n(p) + d(p) + s(p)$$

where, p is the observed point; n(p) is the measurement noise; d(p) is the deformation; and s(p) are the systematic errors, which account for failures in the assumption of identical exterior and interior orientation of the device and stability of the environmental influences. The emittance direction of the laser pulse towards point p is completely parametrised by the horizontal angle β and the vertical angle ζ of emittance and is the same for the two different scans. These angles can be reconstructed from polar coordinates of the xyz points. The coordinate R in the polar coordinate system corresponds to the observation. However, a larger set of points is required to judge the deformation. A shift in the data may still indicate a deformation or the presence of systematic errors.

In order to identify deformation between two scans of different epochs but of the same coordinate system, analysis of the normal vector differences between two points on the clouds is proposed in [15] to check stationarity between the two scans. When the length of vectors is random throughout the data set it indicates stationarity otherwise vectors of similar length and direction indicate movement between epochs.

For deformation detection within segments, initially a best fitting plane is determined for each scan. For corresponding planes in the two epochs, an adjusted plane is estimated. The residuals from this plane are defined and statistically it is checked whether the two planes of each epoch indicate deformation [15]. For this purpose, functional and stochastic models are designed, for the former to describe the expected functional relation between the observations and the plane and the latter, to describe the uncertainties in the observations.

An alternative approach to detect deformation is suggested by [16] and [17] whereby the point cloud information describing an object, and specifically a loaded beam, is used to solve for the analytical model representing the deflection of the beam for each epoch. Once the analytical models at two epochs have been determined, the deflection of the beam can be calculated from their difference. Comparisons between external benchmark measurements, such as digital photogrammetry, have shown that the laser scanner results are about tenfold more accurate than the advertised single-point precision.

5. Deformation Applications

While deformation monitoring with conventional surveying is superior in accuracy compared to terrestrial laser scanning where individual sample points have low precision (e.g. ±2mm to ±50mm), modelling of the entire point cloud may be effective for representing the change of shape of a structure. A modelled surface will be a more precise representation of the object than the un-modelled observations. A number of case studies are presented to highlight the potential application of laser scanners to deformation monitoring given that their accuracy can be greatly improved by exploiting the 3D point clouds with simple modelling techniques. The purpose of these experiments is firstly, to assess the sensitivity of laser scanners for the measurement of deformation of loaded structures and to investigate their potential for metrology tasks where remote observations are desirable. Analysis of the accuracy of the laser scanners involved computing differences between benchmark observations (e.g. photogrammetry) and laser scanner deflections.

5.1. Deformation monitoring using target points

The simplest means of deformation monitoring is the use of signalised-point measurements. A number of predefined targets are placed on the deforming object and repeated scans are acquired in each deflection epoch. The estimated coordinates of the targets in each epoch are compared against the 'zero'-load case and the deformation vectors are computed. However, in this case of deformation analysis, rigorous statistical evaluation is required in order to verify the significance of the motion.

Such a methodology requires all data be transformed into a common coordinate system. In [18] a deformation experiment is described whereby a number of retro-reflective targets were placed on a deforming object and a number of repeated scans per epoch were acquired by a Cyrax 2500 scanner. Dedicated algorithms defined the centres of the targets at an accuracy of 0.10mm. Prior to the estimation of the deformation parameters, the internal and external accuracy of the scanner was tested and was found good to 0.17mm. This means that for a level of confidence of 95%, deformations of about ± 0.5mm can safely be detected.

The estimated accuracy of the deformation components was ±0.24mm at a confidence level of 95%. Deformation in all targets and in all three directions of X, Y, Z was detected of less than 0.45mm. The repeatability of the results was statistically verified by checking also the differences between the deformations of the same target calculated using repeated scans, which were acceptable in almost all cases. Although the above results show clearly that terrestrial laser scanning can detect sub-millimetre motions, the single point accuracy of targets is much higher when conventional surveying is implemented. The main advantage of the technology is the full surface representation and this is being addressed in the following two experiments.

5.2. Deformation of loaded beams

A methodology for measuring structural deformation, relying on theoretical aspects of beam mechanics and implemented by constrained least-squares curve fitting, has been developed by [16]. It is shown in two structural deformation-monitoring experiments, involving beams loaded in a load-testing frame and a field case involving the span of a timber bridge, that this modelling avoids the arbitrary nature inherent in some other methods, such as gridding. All experiments were controlled with convergent digital photogrammetry.

The first experiment involved the controlled loading of a timber beam on an indoor test frame. The loading was applied by a hydraulic jack that was positioned at the centre of the beam. A total of eight load increments were applied and the total downward vertical deflection measured at the centre of the beam was approximately 40mm. Two laser scanners were used during these experiments: a Cyra Cyrax 2500 and a Riegl LMS-Z210. All laser data for a single epoch were processed in one adjustment, thus simultaneously solving for the parameters of the analytical models of beam deflection. The mean number of points used for each solution was 7364 for the Cyrax 2500 and 1099 for the LMSZ210. The estimated models using Cyrax 2500 data, compared to the benchmark photogrammetry, give an overall RMS of differences of ±0.29mm and the overall RMS of differences for the LMS-Z210 is ±3.6mm, as shown in Table 1. The maximum RMS is ±5.0mm for the 25mm deflection case. The overall RMS values represent a factor of improvement (in precision) of 21 times for the Cyrax 2500 and 7 times for the LMS-Z210 over the coordinate precision of each laser scanner.

Nominal Vertical Deflection (mm)	RMS of differences (mm)	
	Cyrax 2500	LMS-Z210
5	± 0.12	± 3.6
10	± 0.14	± 4.1
15	± 0.47	± 3.2
20	± 0.26	± 2.3
25	± 0.24	± 5.0
30	± 0.27	± 5.0
35	± 0.30	± 2.7
40	± 0.34	± 1.4
Total RMS	± 0.29	± 3.6

Table 1: RMS of differences between TLS-derived and photogrammetry-derived vertical deflections using 13 targets per deflection case

Similar results were obtained at the experiment of the concrete beam (Fig. 1) which was loaded in increments up to 240kN (approximately 13mm of vertical deflection). The Riegl LMS-Z210 laser data achieved the estimation of the model parameters at an accuracy of ±2.4mm level (1σ).

A third experiment involved placing large weights over a span of an ageing timber bridge and measuring the deformation at critical sites on the various structural members. A Riegl LMS-Z210 TLS was used to acquire a scan per load epoch.

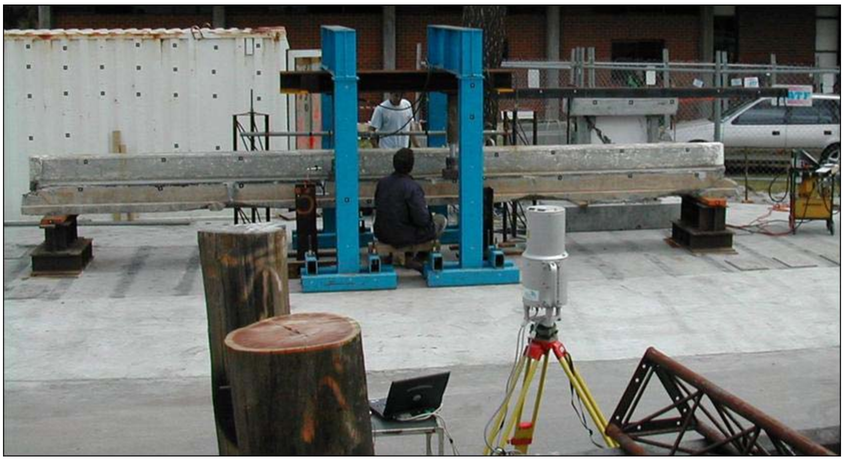

Fig. 1: Concrete beam and the Riegl LMS-Z210

The derived vertical deflections from the laser scanner data were computed using the estimated parameters of the analytical model. A comparison of the laser derived deflections and the photogrammetric derived deflections gave RMS differences ranging from ±2.6mm for the stringer (longitudinal timber member underneath the bridge deck) closest to the scanner to ±13.0mm for the stringer furthest from the scanner, which are at the same level of accuracy as the results of the laboratory-based experiments.

5.3. Deformation of a lock

The aim of the experiment described in [15] was to estimate any deformation caused by the change in water level to a small sea-lock (Fig. 2) that connects the main shipping channel from Amsterdam to the open North Sea. Using the HDS2500 laser scanner at a fixed position, two scans were obtained in a short time interval.

The processing of the data initially included comparison between points, since the two scans were acquired from the same position. However, the range differences showed systematic movement which although were within the accuracy specifications for single measurements they were not expected in the specific parts of the lock. Possible explanations were attributed to strong wind or instability of the instrument during the scanning operation. Therefore, it was performed segmentation to extract homogeneous surface elements automatically. The planes fitted to point cloud from an entire segment were compared between the two epochs. It was shown that from the four segments shown in Fig. 2, the lower test values – indicating stability – are those of segments 1 and 3, whereas the higher test values – indicating movement – are those of segment 2 and 4.

While this is a first indication of deformations, further study showed that the plane model is not appropriate for an entire segment and analysis for smaller regions is preferred. Therefore, the area of one segment was split up into raster cells of equal size. The edge length of the raster was chosen to be 5cm, which leads to roughly 10 points per cell.

This was performed for both epochs and obtaining the covariance matrices for each set of plane parameters deformation analysis was performed. One test statistic was provided for each cell and was checked against the critical value using the χ_2-distribution with 3 degrees of freedom. It was found that 1234 cells were accepted, i.e. found to be stable, whereas 444 cells were rejected, i.e. a movement was detected with a significance level of 5%. The differences from the reference plane of the first epoch varied from 0mm to 20mm for the stable cells and from 9mm to 21mm for the moving cells.

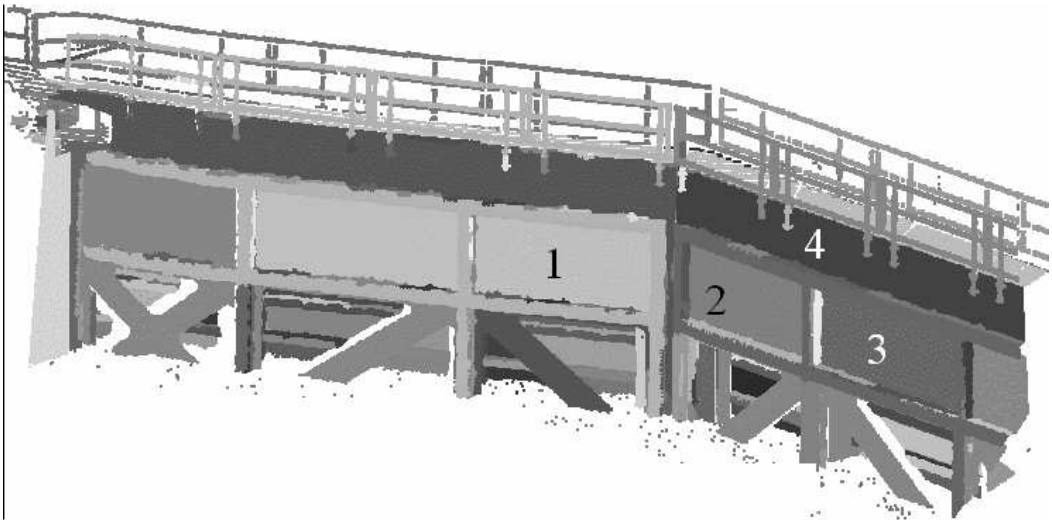

Fig. 2: Point cloud representing the lock and segmentation of the data into planes

6. Concluding Remarks

The feasibility of laser scanning for deformation monitoring and the issues that have to be taken into account were discussed in this paper. Clearly, the accuracy offered by conventional surveying techniques is superior compared to the single point accuracy of commercial terrestrial laser scanners. However, the use of modeled surfaces rather than single points is the key to deformation monitoring using laser scanning. The high speed in obtaining enormous sets of 3D dense data from the surface of a deforming object makes laser scanning at least a complementary technology for monitoring deformations.

The importance of assessing the metric integrity of any sensor for industrial metrology applications, such as deformation monitoring, is critical and therefore, the development of calibration procedures and systematic error modelling is also of significance for laser scanner instruments. A review on scanner calibration indicates that is not always adequate to perform calibration in terms of a set of independent procedures because while these can demonstrate existence of systematic errors they cannot necessarily provide the exact nature of these errors. Self-calibration schemes can be more rigorous in identifying systematic errors in the observables. Nevertheless, independent testing and calibration despite the manufacturer having pre-calibrated the instrument is necessary for reliable deformation results.

The indicative case studies presented in this paper demonstrate that terrestrial laser scanners are capable of detecting deformation motions. When special targets on the surface of the deformable object are used motions of about ± 0.5mm are detectable. However, the main advantage is the full surface representation whereby results can be achieved of the same accuracy league as close-range photogrammetry (at least, for non-metric cameras). Finally, statistical deformation analysis is essential to implement in the laser data analysis rather than simple thresholding in order to asses the results.

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