

**DETECTION OF STRUCTURAL DEFORMATION FROM 3D
POINT CLOUDS**

JONATHAN NYOKA CHIVATSI

UNIVERSITI TEKNOLOGI MALAYSIA

DETECTION OF STRUCTURAL DEFORMATION FROM 3D POINT CLOUDS

JONATHAN NYOKA CHIVATSI

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To my beloved wife, Cidi

To my lovely Sons and Daughters

To my caring Parents

To my wonderful Family

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ABSTRACT

The observation and detection of movements of man-made structures is a noble task in engineering survey, for it is geared towards preservation of life and property. Many different methods exist for detection and monitoring deformations. These methods have served humanity very well over the years. However, most of these methods are point based. Terrestrial laser scanning allows for the monitoring of the whole surface of a structure. All these methods require data to be compared between two or more campaigns. For the data set to be comparable, it needs to be transformed not only into the same coordinate system, but also into the same computational base. An analysis of the stability of reference points by global congruency testing, coupled with the S-transformation enable this to be achieved. In this thesis, the Total station and terrestrial laser scanner were used to detect deformation of a building. The global congruency test was used to detect deformations between two epochs, followed by a single-point analysis which is used in the localization of deformations. After determination of stable scan stations, point cloud data from two epochs was transformed into the same computational base. This enabled point to surface and surface to surface deformations analysis to be undertaken.

ABSTRAK

Pemerhatian dan mengesan pergerakan struktur buatan manusia adalah satu tugas yang mulia dalam ukur kejuruteraan, kerana ia adalah ke arah pemeliharaan nyawa dan harta benda. Banyak kaedah yang berbeza wujud untuk mengesan dan ubah bentuk memantau. Kaedah-kaedah ini telah berkhidmat manusia dengan baik selama ini. Walau bagaimanapun, sebahagian besar daripada kaedah ini adalah titik berasaskan. Pengimbasan laser daratan membolehkan pemantauan seluruh permukaan struktur. Semua kaedah ini memerlukan data untuk dibandingkan antara dua atau lebih kempen. Bagi data yang ditetapkan untuk dibuat perbandingan, perlu berubah bukan sahaja ke dalam sistem yang sama menyelaraskan, tetapi juga menjadi asas pengiraan yang sama. Analisis kestabilan titik rujukan oleh ujian keselarasan global, ditambah pula dengan S-perubahan ini membolehkan untuk dicapai. Dalam projek ini, stesen Jumlah dan pengimbas laser daratan yang digunakan untuk mengesan perubahan bentuk bangunan. Ujian keselarasan global telah digunakan untuk mengesan ubah bentuk di antara dua zaman, diikuti dengan analisis titik tunggal yang digunakan dalam penyetempatan ubah bentuk. Selepas penentuan stesen imbasan stabil, data titik awan dari dua zaman telah berubah menjadi asas pengiraan yang sama. Ini titik JavaScript untuk permukaan dan permukaan ke permukaan analisis ubah bentuk yang akan dijalankan.

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LIST OF ABBREVIATIONS

3D	Three Dimensional
DGPS	Differential Global Positioning System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
FOV	Field Of View
SNR	Signal to Noise Ratio
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
ATR	Automatic Target Recognition
NURBS	Non Uniform Rational Basis functions

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Any object, natural or man-made, undergoes changes in space and time (Chen, 1983). By taking measurements on the object, the changes or deformations on the deformed body can be understood and modelled.

The need for regular monitoring of structures will not be overemphasized. Humanity has given us the old saying: prevention is better than cure. Therefore, it is important to regularly monitor the robustness and any changes of structures.

In the geomatic world, many methods have been devised to monitor displacements and deformations of structures. Most of the deformation monitoring surveys involves finding the differences between two datasets for the same object made in different time moments (epochs). However, most of the methods only monitor a few discrete and well signalized points on the surface of the objects. This means that the deformed object has to be accessed, which, depending on the stability status of the object to be measured, poses a danger to the Geomatic Engineer.

Terrestrial Laser Scanning (TLS) offers a rapid and dense measurement of huge amounts of object points, enabling surface deformation analyses to be made on entire object's surface object's surfaces exploiting the high data redundancy. TLS is a remote sensing measurement technology; therefore, the direct object accessibility is not required

and the influence of installation of control points or other sensor compositions onto the observed object is minimized (Vežočník et al., 2009).

1.2 Problem Statement

In recent years, Terrestrial laser scanning (TLS) has become increasingly used in different engineering surveying applications, including in the field of displacement and deformation monitoring. Despite the growing number of research activities in this field, the efficacy of Terrestrial Laser scanning has not been completely evaluated, and still the workflow and accuracy of TLS is a very open area of investigation (Reshetyuk, 2006).

The ability to perform a rapid and dense measurement of huge amounts of object points is itself, an overriding advantage of TLS in comparison to other sensor technologies and point-wise monitoring approaches, where deformation evaluation is limited to few discrete and well signalized points. When two sets of point clouds of the deformed object are obtained from different epochs, the data can be modelled separately and used for a deformation analysis, employing the available statistical methods and exploiting the high data redundancies of TLS.

1.3 Objective of the Study

The aims of this study are

- (i) To enable the author have a clear understanding of the procedures necessary to conduct a three dimensional deformation analysis.
- (ii) To assess the feasibility of using Terrestrial Laser Scanning, using the Leica Scan Station c10, to analyse deformations of building structures.

(iii) To conduct point to point deformation analysis using Total Station observations and use these results to detect surface deformations from Terrestrial Laser Scanning data.

1.4 Scope of the Study

In this study, two sensors, a Total Station and a Terrestrial laser scanner will be used to collect data in at least two epochs. Each of the two sensors has its own advantages; the point positioning accuracy of the Total station and the large amount of surface data of the total station. The aim of using the two sensors is to make use of their inherent advantages in order to have a quality result. No attempt will be made to compare them.

The Total Station data will be processed by way of network adjustment, while the Terrestrial scanning data will be processed using the Manufacturer's software. Some of the terrestrial laser scanning data will be processed using Cloud Compare software. A MATLAB program will be developed to process most of the Total Station data.

Deformation analysis will be restricted to geometrical analysis methods to detect deformations on the structure. The physical analysis procedures will not be employed.

While calibration of instruments is an important step in the process of deformation monitoring, this procedure will not be carried out. For this purpose the Manufacturer's parameters will be assumed.

1.5 Significance of the study

Regular monitoring of deformations of both natural and anthropogenic spatial structures is important due to the enormous risk for human life in the case of failure. In combining Total Station and Terrestrial laser scanning observations for monitoring movements, one is assured of the point accuracy of selected points on the structure, as

well as a complete surface of closely knit points. Out of this point cloud a dense and accurate surface model can be generated which describes the actual surface. A comparison of two or more of such surface models from different epochs is able to show the deformation of the entire surface. The results can be analysed using the different deformation analysis approaches that have evolved (e.g., Delft, Fredericton, Hannover, Karlsruhe, München (Chrzanowski, 2006)) to highlight zones with higher vulnerability for deformations, which afterwards may be surveyed more frequently with other equipment, like motorized total stations with automatic target recognition.

The second relevant aspect is closely related to the economics of construction and management. The expenses of conceivable restoration may go beyond bounds; therefore, the causes for the occurrence of deformation should be discovered and prevented on time.

Considering that TLS is a relatively new technique, the study also provided an understanding of the operations of Terrestrial Laser scanning equipment and the techniques for Deformation monitoring. The advantages of determining the deformation of structures by comparing surfaces obtained from TLS point clouds have been promulgated by many researchers (Tsakiri et al., 2006).

1.6 Related work

The millimetre to sub-millimetre accuracy required in deformation accuracy calls for stringent calibration procedures for the equipment concerned. In Tsakiri et al (2006), a discussion is made on the issues influencing the feasibility of Laser scanning in deformation monitoring. Demonstrations with a number of case studies are made. Of critical importance to the TLS technique, is the initial evaluation of the scanner's performance within a calibration scheme. Appropriate statistical control procedures have to be made, irrespective of whether or not the Manufacturer has pre-calibrated the equipment. This ensures the metric integrity of the instrument for deformation analysis. In this paper a review of the different methods of calibration, including both the

independent methods and self-calibration methods is made. The use of raw observables in self calibration, as opposed to the scanner's Cartesian coordinates, is given importance. Calibration can be done either indoor or outdoor.

For deformation monitoring applications it is more practical 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.

Several case studies have been presented in Tsakiri et al (2006) to evaluate the potential of Terrestrial scanning as a technique for deformation monitoring. The studies demonstrated that the accuracy offered by conventional surveying techniques is superior compared to single point accuracy of commercial terrestrial laser scanners. It is noted, however, that the use of modelled surfaces rather than single points is the key to deformation monitoring using laser scanning, exploiting the huge amount of 3D point clouds data with simple modelling techniques. At the very least, the enormous sets of 3D data from the surface of a deforming object makes laser scanning a complementary technology for monitoring deformations.

It is concluded 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 $\pm 0.5\text{mm}$ are detectable. Statistical deformation analysis is also essential to implement in the laser data analysis.

Deformation monitoring of structures requires spatial measurement techniques that are reliable, accurate, low-cost and easy to implement. A number of techniques possess these characteristics. However, majority of these techniques require the use of predefined targets, which may not be feasible in some cases, for example when the structure is inaccessible. In another research (Tsakiri et al., 2006, Tournas and Tsakiri, 2008) a methodology was presented of measuring structural deformation, based on acquisition of terrestrial laser point clouds from a deforming object without the use of predefined targets. Instead of using targets, a number of stationary control points located in the surrounding area of the object are used, which were identified automatically on photographic images taken during the laser scanning data acquisition, using a high

resolution CCD camera mounted on the scanner device. The purpose of the methodology was to investigate the deformation of an object in two or more discreet epochs and to describe its application in laboratory experiments on a model of an ancient temple under stress caused by controlled motion.

In conclusion, the method was found suitable, especially to objects that make the use of signalized targets impossible, such as tall buildings or objects with complex surfaces.

Deformation that is large compared to the measurement noise is easier to track. However, in Lindenberg and Pfeifer (2005), a comparison was made of scans of an object, where the possible deformation is in the order of measurement noise. The object selected was a small sea lock (Figure 2.1) in the sea entrance of the Amsterdam harbour, which connects the main shipping channel from Amsterdam to Open North Sea. Two scans were obtained within a short time interval, without physically changing the position of the scanner. The scanner used in the experiment was a pulsed Leica HDS 2500.



Figure 1.1 Point cloud representing points from the first epoch (Lindenberg and Pfeifer, 2005)

Different methods were used in the analysis of the point cloud data. Segmentation was the first method to be used. The purpose of this method was to group points with similar properties, using a region growing technique for segmentation of a planar patch. Another method used in this research was the direct comparison of observed points, since the scanner was stationary during the two scans. The other method used to detect deformation was using the unit normal vector of the planar surface.

In these experiments, the surface modelling method was used for monitoring and estimation of deformation of the sea lock. This was achieved by finding a mathematical parameterization for planar patches. A least squares approach was used to model the planar surface parameters. Statistical tests were then used to assess the fitness of the model to the observations and also to test if the two planes in a single epoch show a deformation or not. The least squares mathematical model, statistical tests and analysis of the data and results are described in the paper.

In Alba et al (2006), the feasibility of monitoring deformations of a large concrete dams using Terrestrial Laser scanning was assessed. A test field was established on the dam of the Cancano Lake in Valtellina, Italy. This was made up of a local geodetic network for georeferencing all data acquired at different times. A large number of retro-reflecting targets were positioned and measured by a total station in the local datum. Targets were measured and also captured by the scanner. Some of the targets were placed on the dam structure to be used as independent check points, and some were placed in the surrounding area to act as ground control points. Three measurement campaigns were conducted using two laser scanners: a long range Riegl LMS-Z420i and a medium range Leica HDS 3000. The reported analyses were focused on two main problems. The first problem was the accuracy and the stability of georeferencing, which is fundamental to make comparisons between different multi-temporal scans. The second problem was the computation of deformation based on the acquired point-clouds. Two approaches were also presented for the analysis of surface displacements, including the shortest distance between the consecutive point clouds (one being a surface model) and additionally displacements computed by comparing two

regular grids of the dam face. In this study it was concluded that the stability of the reference frame is of great importance in order to separate the displacements from the noise produced by errors within the georeferencing process.

Deformations of a structure can occur, either after the construction is completed, i.e. between two measurement epochs, or before completion (Gosliga et al., 2006). The latter situation is related to a change in the design model of the structure. In this study, a procedure was developed, implemented and tested to detect deformations in a bored tunnel. The procedure involved, first fitting the cylindrical model to a point cloud consisting of several registered terrestrial laser scans using a linearized iterative least squares approach. This resulted in approximately optimal values for the tunnel model. Thereafter, deformations with respect to the tunnel model or between epochs were determined by means of a statistical testing procedure (i.e. the Delft method). Point wise deformation analysis was performed by comparing surface patches. Results obtained showed that the tunnel was not so much oval as was expected after construction, but rather that single tunnel segments showed different deviation patterns.

The advantage of using Terrestrial laser scanning above other traditional surveying methods is that it allows for the rapid acquisition of millions of scan points representing the whole surface of the object considered. However, it is still a big challenge to obtain accuracies and precisions in the millimeter level when quantifying deformation of an object between epochs. In Lindenberg et al (2005), two main steps were distinguished which together strongly contribute to obtaining results close to the Signal to Noise Ratio(SNR) of scanners. The first step is obtaining for each epoch a point cloud of optimal quality, while the second 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 in the paper using several examples from mainly tunnel monitoring projects located in the Rotterdam area.

It was concluded in the paper that still; many questions remain unanswered on the use of Terrestrial laser scanning. The first question relates to the a priori characterization of the quality of individual points which was still under investigation but not yet available. It was noted also that most algorithms used for processing such

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.

Besides these case studies, many authors have applied TLS for the detection of deformations in the controlled environments or experiments with simulated values of displacements, e.g., Tsakiri et al (2006). In this way, the actual displacements and the measurement noise can be distinguished more easily, also because the effects of meteorological conditions can be neglected. Furthermore, the quality and stability of the reference frame also is not particularly addressed in these studies (it is assumed to be stable) mainly due to the fact that complementary surveying technologies must be implemented in the measurement setup in order to tackle the problem of datum correctly (Vežočník et al., 2009).

1.7 Organization of Chapters

This project is organized into seven chapters. In chapter two, a background of deformation surveys is given. Here, the different techniques of deformation survey are briefly reviewed, followed by a more detailed overview of tacheometry and Terrestrial laser scanning methods. Chapter three deals with the data processing steps of the raw total station and terrestrial laser scanning data, in preparation for deformation analysis. The deformation analysis techniques for the two data types are discussed in chapter four. In chapter five, the research methodology used in the research is given. Chapter six highlights the implementation of the methodology. The results of the implementation are discussed in chapter seven. Finally, in chapter eight, a conclusion is given with recommendations.

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