A Review of the Use of Terrestrial Laser Scanning Application for Change Detection and Deformation Monitoring of Structures

Wallace Mukupa*, Gethin W. Roberts, Craig M. Hancock, Khalil Al-Manasir

Department of Civil Engineering, The University of Nottingham Ningbo, China
199 Taikang East Road, University Park, Ningbo 315100, China.

*Corresponding Author. Email: wallace.mukupa@nottingham.edu.cn

Abstract

Change detection and deformation monitoring is an active area of research within the field of engineering surveying as well as overlapping areas such as structural and civil engineering. The application of Terrestrial Laser Scanning (TLS) techniques for change detection and deformation monitoring of concrete structures has increased over the years as illustrated in the past studies. This paper presents a review of literature on TLS application in the monitoring of structures and discusses registration and georeferencing of TLS point cloud data as a critical issue in the process chain of accurate deformation analysis. Past TLS research work has shown some trends in addressing issues such as accurate registration and georeferencing of the scans and the need of a stable reference frame, TLS error modelling and reduction, point cloud processing techniques for deformation analysis, scanner calibration issues and assessing the potential of TLS in detecting sub-centimetre and millimetre deformations. However, several issues are still open to investigation as far as TLS is concerned in change detection and deformation monitoring studies such as rigorous and efficient workflow methodology of point cloud processing for change detection and deformation analysis, incorporation of measurement geometry in deformation measurements of high-rise structures, design of data acquisition and quality assessment for precise measurements and modelling the environmental effects on the performance of laser scanning. Even though some studies have attempted to address these issues, some gaps exist as information is still limited. Some methods reviewed in the case studies have been applied in landslide monitoring and they seem promising to be applied in engineering surveying to monitor structures. Hence the proposal of a three-stage process model for deformation analysis is presented. Furthermore, with technological advancements new TLS instruments with better accuracy are being developed necessitating more research for precise measurements in the monitoring of structures.

Keywords: Terrestrial laser scanning, change detection, deformation monitoring, registration, georeferencing, review

1.0 Introduction

Geodetic monitoring of structures is a common practice in the field of engineering surveying (Mechelke *et al.,* 2013). Monitoring structural deformation is one of the major concerns when dealing with structures such as bridges, tunnels, dams and tall buildings (Han *et al.,* 2013). These engineering structures are examples of structures that are routinely surveyed and monitored for their stability as they are subject to deformation due to factors such as changes of ground water level, tidal phenomena, tectonic phenomena, etc. (Erol *et al.,* 2004). Periodic monitoring of the structural response is necessary to rationally secure and maintain the safety of structures (Park *et al.,* 2007). The knowledge about types, characteristics and scales of structural deformations is essential when defining their nature and for the consequent verification of potential permanent damage possibilities or eventual destruction of structures (Vezocnik *et al.,* 2009). Deformation monitoring of the static and dynamic behaviour of engineering structures is an active area of study due to the impact that these structures have on the landscape where they have been built and the potential damage they can cause in case of a malfunction (Gumus *et al.,* 2013; Schneider, 2006). Within the field of engineering surveying, especially in the area of deformation and displacement measurement of structures, traditional point-wise surveying methods are mostly used. Vertical displacements and elevations are measured by high precision levelling whilst the spatial displacements and movements are derived by total stations or theodolites (Lovas *et al.,* 2008).

From the past to present, several studies have been carried out on the monitoring of engineering structures and different geodetic techniques have been applied to monitor structures. There exists a vast literature on monitoring of structures and detection of deformations using geodetic and geotechnical techniques (Chrzanowski *et al.,* 2011). Deformation monitoring using TLS is gaining

attention due to the high point density and spatial resolution that can be acquired in a short time, but the use of laser scanning for deformation monitoring is still in its infancy (Walton *et al.,* 2014). Driven by progress in sensor technology, computer software and data processing capabilities, TLS has recently proved a revolutionary technique for high accuracy 3D mapping and documentation of physical scenarios (Gikas, 2012) and a wide range of other application fields involving change detection and deformation monitoring of structures (Vezocnik *et al.,* 2009; Lindenbergh *et al.,* 2009; Scaioni, 2012). The application of TLS surveying technique is broadening in the civil engineering industry for example Lovas *et al.* (2008). TLS has also seen some developments in, for instance, more methods being available to characterize the quality of acquired data and it has become more and more known as a surveying technique to a wider audience (Lindenbergh, 2013). The principle of laser scanning technology in terms of operation and application has been presented by several authors (Lichti *et al.,* 2002a; Staiger, 2003; Reshetyuk, 2009; Shan and Toth, 2009; Abbas *et al.,* 2013). TLS has received attention because it offers numerous measurement benefits ranging from direct 3D data capture from a single instrument setup, remote and noncontact (targetless) operation, and dense data acquisition (Gordon and Lichti, 2007). The growing importance of this technology is also mirrored by the establishment of FIG Taskforce 6.1.5 on 'Terrestrial Laser Scanning for Deformation Monitoring' and ISPRS Working Group V/3 on 'Terrestrial Laser scanning' (Tsakiri *et al.,* 2006). This paper reviews the trends in the application of TLS in change detection and deformation monitoring and proposes a hybrid three-stage process of deformation analysis of laser scanning data based on the existing techniques. A discussion on registration and georeferencing in TLS is also presented as these initial data processing steps are essential prior to 3D modelling or analysis in applications such as change detection and deformation monitoring. Furthermore, Wujanz *et al.* (2013) state that a critical component within the process chain of deformation monitoring is the transformation of subsequently captured point clouds into a reference respectively superior coordinate system.

2.0 Change Detection and Deformation Monitoring

The purpose of change detection is to determine if the geometric state of a scene has changed. Change detection looks for a binary answer, has a situation changed or not whereas deformation analysis looks for a quantified change (Lindenbergh and Pietrzyk, 2015). Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times. Change detection has an old research history and wider applicability in the field of remote sensing. A variety of change detection techniques have been developed in the remote sensing field and reviews of their applications and recommendations for selection of suitable change detection methods have been reported (Lu *et al.,* 2004). However, as TLS has matured as a surveying technique, various researchers have carried out studies to identify changes in a scene or on an object's surface from repeated laser scanning surveys. Actually, change detection, deformation analysis and structural monitoring is different terminology for strongly related topics and in terms of TLS what they all have in common is that they all compare point clouds of the same scene or object, but acquired at different epochs (Lindenbergh, 2013).

Deformation monitoring is the systematic measurement and tracking of the alteration in the shape or dimensions and position of an object as a result of the application of stress to it. Deformation monitoring is a major component of logging measured values that may be used for further computation, deformation analysis, predictive maintenance and alarming (Dunnicliff, 1993). Deformation monitoring has also been defined as the surveying of a region of interest at different points in time and identifying geometric changes based on the captured data in between the respective epochs. Furthermore, stating that a stable reference frame is required which is described by immovable control points and that in order to achieve this prerequisite, deformed regions need to be identified within the area under investigation (Wujanz *et al.,* 2013). There are several techniques for measuring deformations. These can be grouped mainly into two as geodetic and geotechnical techniques. TLS is an example of a geodetic technique (Chrzanowski *et al.,* 2011).

3.0 Terrestrial Laser Scanning Change Detection

Different point cloud comparison techniques have been used by many researchers to detect change between sequentially gathered point clouds (Girardeau-Montaut *et al.,* 2005). The cloud to mesh method has been used with success to investigate structural and surface deformation. Gridded data sets can be compared to produce a DEM of difference, which highlight areas of loss or accumulation (Barnhart and Crosby, 2013). Many authors have actually reported methods implemented for surface modelling of a deforming object that involve simple gridding (Tsakiri *et al.,* 2006). However, isolating regions of interest and creating DEMs or surface models is time consuming and requires interpolation. Furthermore, a topographic data reduction occurs when point cloud data is reduced from 3D to 2.5D. Monserrat and Crosetto (2008) also stated that some authors have performed deformation studies by directly comparing DEMs from different TLS campaigns. Though this approach is easy to implement using commercial software, general purpose algorithms are often not sufficient for specific purposes such as change detection. For instance it is not appropriate to use the built-in PolyWorks software functions for calculation of shortest distance as the result is normally an underestimation of the total displacement or change (Walton *et al.,* 2014). Furthermore, the approach of comparing DEMs has two important limitations. Firstly, it has limited sensitivity to small deformations. Secondly, since the DEMs are typically defined on a 2D support, i.e. $z=f(x,y)$, the difference between DEMs basically provides a 1D deformation measurement in the z direction. Given the 3D nature of the TLS point clouds, this represents an important limitation of this approach (Monserrat and Crosetto, 2008).

The cloud to cloud methods have also been used to directly compare point clouds but they often do not return signed (-/+) displacements, which are required for many applications. Although both cloud to mesh and rotated DEMs of difference techniques enable comparisons of complex point cloud scenes, they require a high degree of data processing and isolation to work effectively (Lague *et al.,* 2013). Cloud to mesh comparisons provide good approximations of surface change, yet they do not take into account the local orientation of the surfaces represented by the point clouds. Furthermore, cloud to mesh and DEMs of difference methods are labour and time intensive because areas of interest must be carefully isolated and treated in the TLS data processing workflow to create reference meshes and DEMs (Barnhart and Crosby, 2013). Meshing TLS data is not only a limitation as a second interpolation of the data, which adds a level of error to the data, but meshing can also create erroneous surfaces (Walton *et al.,* 2014). In view of some of the limitations of the change detection techniques mentioned above, Lague *et al.* (2013) present a new change detection algorithm called Multiscale Model to Model Cloud Comparison (M3C2) which combines for the first time three key characteristics: it operates directly on point clouds without meshing or gridding, it computes the local distance between two point clouds along the normal surface direction which tracks 3D variation in surface orientation and it estimates for each distance measurement a confidence interval depending on point cloud roughness and registration error. Worth considering from Lague *et al.* (2013) are the three main sources of uncertainty in point cloud comparison for change detection which include:

i. Position uncertainty of point clouds as a result of the instrument used and that the case may be worse with increase in distance and incidence angle.
ii. Registration uncertainty between the point clouds.
iii. Surface roughness related errors caused by the difficulty to reoccupy exactly the same scanning position (Alba *et al.,* 2006; Gonzalez Aguilera *et al.,* 2008) between surveys.

In summary, a common technique to perform change detection on TLS point cloud data is to compute and compare distances between point clouds at different epochs. It can be done either directly using point cloud data or by creating an intermediary model on top of the points. Cloud to mesh and mesh to mesh distance measurement techniques have been very well studied and demonstrated (Girardeau-Montaut *et al.,* 2005) and in order to avoid repetition of the same information on change detection techniques, the reader of this paper is referred to Lague *et al.* (2013). It is also worth noting that in Hancock *et al.* (2012) a preliminary study was undertaken aimed at change detection of fire-damaged concrete using TLS intensity data.

4.0 Terrestrial Laser Scanning and Deformation Monitoring

Deformation monitoring is typically undertaken with point-wise surveying techniques, such as total station or GNSS (Lovas *et al.,* 2008). However, the capability of TLS to provide high spatial resolution three-dimensional data with speed and accuracy has considerably gained the attention of engineers in recent years and TLS has become increasingly used in different engineering surveying applications such as structural deformation monitoring (Abbas *et al.,* 2013). The motivation is that, TLS as applied in deformation monitoring offers advantages such as remote measurement and therefore, the direct object accessibility is not required (Vezocnik *et al.,* 2009). Other advantages of TLS include a permanent visual record and high spatial data density as does photogrammetry although the requirement of targets or other sensor compositions installed in the monitoring scene in minimised (Gordon *et al.,* 2003; Lichti *et al.,* 2002a).

Due to some of the advantages mentioned above, in the last few years there has been an increasing interest in exploiting TLS data for deformation monitoring. However, when working with TLS data for quantitative analysis for deformation measurement or change detection, it is not sufficient to just look at raw point cloud data, post-processing is necessary to generate usable data (Walton *et al.,* 2014). Actually, the exploitation of the high redundancy provided by TLS tools is key to achieving good deformation measurement performance with TLS data and often requires the development of ad hoc tools (Monserrat and Crosetto, 2008). In the same vein other researchers have also stated that new ways to fully exploit the huge quantity of information provided by TLS point clouds are still needed (Abellan *et al.,* 2009; Lindenbergh, 2013). Traditionally, deformation analysis studies are based on displacement data obtained using conventional surveying techniques as mentioned. These methods can detect millimetre level displacements and they measure the displacements at a limited number of points (Gikas, 2012).

In contrast to conventional surveying techniques of superior accuracy, the single point precision of medium to long range TLSs varies from ±2mm to ±25mm, depending on the instrument model and observation conditions. However, the theoretical precision of a surface derived from spatially dense point cloud data is substantially higher than the single point precision (Tsakiri *et al.,* 2006; Gordon and Lichti, 2007). Furthermore, Gordon *et al.* (2003) state that techniques may be employed to improve the single point precision of a TLS system. One method involves averaging repeat scan clouds where multiple scans acquired sequentially are averaged to create a cloud that may be two to three times more precise than an individual cloud, according to the root of the number of repeat scans. For example, four repeat scans will theoretically improve the standard deviation of a single point by a factor of two and that this has been empirically verified by Lichti *et al.* (2002b). According to literature there are studies that have examined the potential of TLS in detecting millimetre deformations with success as reported in the subsequent sections of this paper.

In addition, Monserrat and Crosetto (2008) state that the key idea is to overcome the limited precision of the single TLS points by taking advantage of the high redundancy of the observations, i.e. the 3D points and the geometric characteristics of the observed surfaces. An appropriate TLS data analysis method is one which takes full advantage of the high sampling density of the TLS data, guarantees a high observation redundancy for the least squares based estimate and hence a good precision of the estimated deformation parameters (Monserrat and Crosetto, 2008). In a similar vein Gordon and Lichti (2007) state that although individual sample points are low in precision and therefore preclude their use in deformation monitoring, modelling the entire point cloud of high data redundancy leads to a much higher precision of the estimated parameters and an effective way for representing the change of shape of a structure.

Several case studies applying TLS for deformation monitoring of engineering structures and land deformation have been carried out in recent years. The deformable objects that have been studied include different engineering structures such as dams, bridges, tunnels, pipelines, towers, viaducts and many others structures. Some notable case studies are described below:

Alba *et al.* (2006) present some initial results of a project aimed to assess the feasibility of monitoring deformations of large concrete dams by TLS. The study was focused on two main problems: the first one was the accuracy and the stability of georeferencing; the second one was the computation of deformation based on the acquired point clouds. Two approaches are 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. Results showed that the use of the TLS technique can give an important contribution to the deformation analysis of large dams. The first results obtained from data processing were dense and accurate maps of deformations of the dam downstream face. Some maps of deformations derived from comparison of two laser scanned point clouds captured at different times were produced. Furthermore, it is stated that there is need to improve the accuracy of scan georeferencing.

One interesting approach for structural monitoring of large dams by TLS is described by Gonzalez Aguilera *et al.* (2008). The approach proposed in the study dealt with the application of TLS to the structural monitoring of a large dam considering aspects related to the need for accuracy control in georeferencing as pointed out in Alba *et al*. (2006) together with rigorous approaches to model complex structures. The novelty of the approach was on the utilization of the Radial Basis Function (RBF) for the surface parameterisation as well as the incorporation of an original re-Weighted Extended Orthogonal Procrustes (WEOP) analysis for georeferencing and the accuracy control of the different measurement periods. It is stated that a TLS sensor alone does not suffice in for instance providing a control network of large dams. Some challenges involve the impossibility of scanning the same point in different epochs and the issue of the laser beam width, an observation which was also made in Lichti and Gordon (2004). The 3D modelling approach via RBF improved the nominal precision of the TLS and deformation accuracy results in the range of millimetres were achieved. Accurate georeferencing was achieved by first having a high precision topographic network in order to define a precise and stable reference frame and then applying the WEOP to the range dataset (Gonzalez Aguilera *et al.,* 2008).

In Zogg and Ingensand (2008) load tests of a viaduct (concrete span bridge) were performed to evaluate the fatigue resistance and refine the analytical models. The main objectives of the deformation monitoring by TLS on the viaduct were on one hand to get to know the advantages and limits of the measurement technology for load tests in bridge monitoring and on the other hand to compare TLS with precise levelling in terms of measurement accuracy and detection of deformations. The deformation analysis of TLS data involved both area-wide and discrete analysis using the sphere targets. TLS data were recorded in a local system without any connection to the outside of the viaduct and so local deformations as deflection of the cantilever slab of up to 20mm under a maximum load of about 100 tons were detected by the area-wide analysis whereas the target spheres performed relative deformations of up to 6mm. In contrast to TLS, precise levelling was connected to a transfer point outside the viaduct and absolute deformations of the bridge girder were detected. For TLS, in order to detect absolute deformations of the bridge girder, the data were transformed into the reference height system defined by precise levelling. A comparison of the transformed vertical displacements detected by TLS and the vertical displacements by precise levelling showed that the deformations of the bridge girder were within the same range. Maximum differences between the two measurement methods were around 3.5mm. But considering the mean residuals for the different loading situations, the differences between TLS and precise levelling were less than 1.0mm. TLS was able to detect deformations in mm range.

Lovas *et al.* (2008) present a study which deals with the potential of TLS in deformation measurements involving a bridge load test measurement and a laboratory test. During the controlled load testing of a full-scale steel portal frame, each load phase was captured by TLS. The displacements of dedicated points of the structure were also measured by high-precision inductive transducers for comparison of results from both methods. The structural displacements derived from the TLS data sets were in strong correlation with those obtained from the traditional

techniques. The trend of the curves and the displacement values validated the TLS measurements. The computed maximum vertical displacement was ~35cm in both methods in the fourth load phase. The vertical deflection of the deck was measured directly at the cables using high precision levelling whilst the TLS captured the edge of the girder. The shortcoming of the TLS in displacement measurement was the 5mm (1 sigma) accuracy (high precision levelling is below 1mm) and the difficulty in matching points. For the laboratory measurements, the objective was to capture each of the load phases by TLS, derive the displacements and compare results with traditional high precision measurements. The TLS deformation measurement approaches involved: measuring reflectors, comparing TIN models and measurements on the point cloud which involved fitting lines. The resultant scan of each load phase provided reasonable information about the deformation of the whole frame. The reference value provided by the transducer was 58mm whereas the result from the manual fitting of lines was 60mm with 3mm deviation.

Li *et al.* (2012) describe a new approach for deformation monitoring of a 100m subway tunnel using high-resolution TLS. The new approach involved a point cloud segmentation algorithm based on the normal vectors of the point cloud and surface fitting method based on moving least squares. Measurements were also taken with the optical fiber displacement sensor approach and with a total station so as to compare results with those of TLS. In principle, the TLS methodology involved three main procedural steps. Firstly, registration of point clouds using a linearized iterative least squares approach to improve the accuracy of registration with several control points which were acquired by a total station. Secondly, the registered point cloud was resampled and segmented based on the developed algorithm to select suitable points. Thirdly, the selected points were used to fit the subway tunnel surface and then a series of parallel sections obtained from temporal series of fitting tunnel surfaces were compared to analyse the deformation. The results of the new approach in the Z direction were compared with those of the optical fiber displacement sensor and the results in the X and Y directions were compared with those of a total station. The comparison of results showed the accuracy errors in the X, Y and Z directions to be about 1.5mm, 2mm and 1mm respectively. It was concluded that the new TLS approach meets the demand of high precision subway tunnel deformation monitoring.

Pesci *et al.* (2013) conducted a study on a TLS-based method for fast estimation of seismic-induced building deformations. The method was applied to rapidly detect deformation traces of three buildings damaged by an earthquake. A reliable estimation was achieved by means of experiments and numerical simulations aimed at quantifying a realistic noise level, with emphasis on reduction of artifacts due to data acquisition, registration and modelling. The experiments showed that the observation of an object at high incidence angles leads to distortions that must be quantified and taken into account before evaluating any deformations. According to Lindenbergh and Pietrzyk, (2015) this showed the importance of incorporating the measurement geometry in TLS where high medieval towers of heights close to 100m were scanned from a low position which inevitably led to an unfavourable incidence angle. The expected deformation signal in the study was relatively small and a detailed study of the impact of the incidence angle on the signal to noise ratio was incorporated in the deformation analysis by considering point to point differences between scans from the same wall but acquired from different scan locations. The study showed how to discriminate between an actual deformation and an incidence angle induced distortion in a high and narrow tower. The distortion, which depended on the elevation only had a 5–10cm magnitude difference with respect to the reference primitive whereas the modelling distortion at 90m elevation was 1.6cm. The procedure mapped the point cloud with respect to the expected shape and produced a corresponding significance map of the results and the final outcome was a deformation map for each external wall of the building (Pesci *et al.,* 2013).

In van Gosliga *et al.* (2006), a procedure was developed, implemented and tested to detect deformations in a bored tunnel. Artificial deformations of a cylindrical tunnel wall were detected using a statistical adjusting and testing procedure. It is stated that deformations can occur after construction of the tunnel is finished, i.e. between two measurement epochs, but also deformations

of the completed tunnel with respect to the design model are considered. The methodology used raster partitioning over a cylinder to compare scans of different epochs. The scan data were partitioned into cells and the raster was laid out over the object. During the experiment, scans were taken hours apart with objects added to the surface of the tunnel to simulate deformation (Walton *et al.,* 2014). The tunnel model was fitted to a point cloud consisting of several registered terrestrial laser scans using a linearized iterative least squares adjustment. This resulted in approximately optimal values for the tunnel model. Then deformations with respect to this tunnel model or between epochs were determined by means of a statistical testing procedure. Study results showed that good possibilities exist for deformation analysis using TLS data. The method and computational program developed were able to detect deformations using laser scanning data (van Gosliga *et al.,* 2006).

Han *et al.* (2013) present a TLS approach which was applied to detect the deformation signals of tunnel profiles. In situ control features were used for the registration of tunnel profiles. An efficient approach for automatically extracting tunnel profiles at multiple epochs from raw TLS datasets and establishing an accurate geometric correspondence between them was a key issue. In order to establish point correspondence between the points on the reference (non-deformed) and deformed profiles and to ensure that deformation signals along any profile of interest were identified, a minimum-distance projection (MDP) algorithm was proposed. Simulation tests for the approach were carried out as well as a real case study of the highway tunnel where a wooden stick (6mm thick) was intentionally adhered to the tunnel lining at the second epoch to simulate a deformation signal. The estimated deformation signal in the non-deformed region was randomly distributed with an RMS value of around 0.8mm (MDP analysis uncertainty level). The deformation signal introduced by the wooden stick was detected in the analysis and the estimated displacement for this region was 5.8mm, which was regarded to be within a reasonable confidence interval considering the actual size of the stick (6mm) and ±0.8mm MDP uncertainty. Millimetre level deformation signals of monitored tunnel profiles were successfully detected.

Schneider (2006) describes a method for the deformation analysis of a television tower where in order to determine its bending line the point cloud was cut into N thin layers and projected on to planes, thus transforming the 3D fitting problem into N 2D fitting problems. The bending line was obtained by connecting the centre points of the circles estimated through a circle-fit least squares adjustment applied to each of the N layers. The standard deviation of the centre point coordinates had a higher accuracy than the original laser scanner points which had an average precision of ca. 8mm, with some points having a deviation of up to 3cm. The accuracy of the fitting algorithm was two times better in the Y direction than in the X direction and this was explained by the lateral and depth precision characteristics of the laser scanner. The difference between the tower axes of two epochs which were measured with a time difference of 4 hours was calculated. In this time the temperature changed and the sun started to shine on the tower's surface from the southern direction and so deformations were expected mainly in the Y direction. This was confirmed by the difference between the two bending lines of the two epochs split into the X and Y directions. There was no significant difference noticed in the east-west direction (X) but a change of 13mm per 130m was visible in north-south direction (Y). Results were compared with previous trigonometric measurements and it was confirmed that the television tower had partly tilted.

Vezocnik *et al.* (2009) present an overall and effective approach for long term high precision deformation monitoring of a high pressure underground pipeline using TLS and two conventional surveying techniques i.e. precise tacheometry and GNSS positioning which were used to design and control the stability of the frame for the evaluation of point cloud displacements acquired with TLS. The aim of the study was to challenge the hypothesis which states that the millimetre precision in displacements and deformation monitoring can be achieved in the long term perspective for objects and not only for few signalized points, which is a typical approach when using the point-wise surveying techniques. The geodetic pillars along the pipeline were scanned and a cylinder fitting was conducted from which the representative points along the cylinder axis were determined for

purposes of deformation analysis. By using TLS for the monitoring task, the intention was to exploit the high data redundancy and the contact-less nature of the technology and to check its sensitivity to small scale deformations without directly approaching the object itself. Accuracy results in the range of millimetres were achieved with the approach. The methodology and results achieved were clear evidence of a significant confidence for accepting the initial hypothesis.

Monserrat and Crosetto (2008) describe a new TLS procedure for deformation monitoring based on the least squares 3D surface matching registration algorithm developed by Gruen and Akca (2005). The three main steps of the procedure are: acquisition of the TLS data, global co-registration of the point clouds and the estimation of the deformation parameters using local surface matching. The performance of the approach was tested with a validation experiment where a deformation measurement scenario was simulated using targets of different surface geometry. Measurements were made from two distances, 100m and 200m to the targets using TLS and a total station for comparison purposes. The results showed that for the 100m dataset the majority of the targets had errors below 1cm in the three components of the deformation vectors and rotation errors below 1gon. The results achieved with the 100m dataset were better than those of the 200m dataset. As for the results achieved in a real deformation study related to a landslide test site, 6 deformation parameters were estimated through the proposed approach based on two laser and two topographic campaigns. The estimated errors of the deformation vectors were comparable with those of the validation experiment of which all of them were below 1cm. Similarly, Tournas and Tsakiri (2008) conducted deformation measurements based on TLS point cloud registration. Instead of using targets, stationery control points were captured and automatically detected from images of an external CCD camera that was mounted on the scanner. The image coordinates of the control points were directly used to calculate corresponding 3D object coordinates. It was concluded that the method is appropriate for deformation monitoring.

Teza *et al.* (2007) present a novel approach called the piecewise alignment method for the automatic calculation of the displacement field of a landslide using multi-temporal data provided by TLS. This method consists of an Iterative Closest Point (ICP) algorithm based piecewise alignment of a point cloud to a model generated using data obtained in a previous session. Numerical experiments were carried out and the method was later successfully applied to a real case landslide deformation monitoring study. Tests on real landslides were performed considering two phenomena of similar natures. In one case, the unstable slope was directly observable with a substantially negligible cover and the mean annual displacement was 20cm. In the other, a village was nearly entirely built on a landslide, whose surface was therefore hidden and the average displacement was 2 to 3cm per year. The test demonstrated that the displacement pattern can be effectively reconstructed with a spatial resolution of 5m. In one study area the displacement field was correctly reconstructed with good accuracy whereas in the other, the uncertainty was high and only the calculations on relatively few sub-areas provided reliable results. It was proposed that in order to improve the performances of the piecewise alignment method, it is necessary to minimize the number of areas left unscanned, above all in the urban sites where many shaded areas are present as it would allow an improvement of the spatial resolution. It was also stated that a dominance of the georeferencing error should be prevented.

In Abellan *et al.* (2009), a study was undertaken where the aim was twofold. Firstly, to develop a method that is able to detect millimetric and centimetric scale deformation on rock slopes using TLS and secondly, to apply this method to detect a precursory deformation on a real falling slope. An outdoor experiment with controlled conditions of range and deformation was performed to ascertain if the TLS instrumental error is small enough to enable detection of precursory displacements of millimetric magnitude. Two different data analysis techniques were employed involving the analysis of the original unprocessed datasets and a filtering technique based on the average value of the Nearest Neighbours. Finally, these techniques were applied to the detection of the precursory deformation of a $50m^3$ rockfall on a basalt rockface. Results showed that millimetric changes cannot be detected by the analysis of the unprocessed datasets. Displacement

measurements are improved considerably by applying Nearest Neighbour averaging, which reduces the error (1σ) up to a factor of 6. This technique was applied to displacements prior to the rockfall. The maximum precursory displacement measured was 45mm, approximately 2.5 times the standard deviation of the model comparison, hampering the distinction between actual displacement and instrumental error using conventional methodologies. Interestingly, the precursory displacement was clearly detected by applying the Nearest Neighbour averaging method. The results showed that TLS can detect millimetric displacements prior to failure.

Wujanz *et al.* (2013) present a method to automatically determine geometric changes between several epochs captured by TLS. The method proposed a point based matching methodology, which conducts the Iterative Closest Point (ICP) algorithm for correspondence search within all octree cells and does not use artificial targets for instance. The method addresses a drawback of ICP-based approaches in their vulnerability against deformed areas which leads to erroneous results in registrations. The method solves the problem through identification of existing deformation within datasets by comparison of distances between corresponding points within octree cells and finally rejects them during computation of transformation parameters. The method combines the four points congruent sets and DefoScan++ algorithms as a robust two-tiered procedure for fully automatic deformation monitoring. The capability of the developed method was tested on practical data of a brim within a quarry. Blasted material was removed from the area and a scan was acquired before and after material removal. The position of the scanner was constant for both scans so that reference values for transformation parameters were obtained and in order to simulate data acquisition in different epochs the coordinate system of the second dataset was modified. The achieved results of the method were verified by comparison to a reference dataset. Dependencies of the outcome on the octree cell size were established while the area that contained deformation was identified in all cases.

Mechelke *et al.* (2013) describe a TLS based geodetic deformation monitoring system that was developed. The monitoring system consists of a TLS sensor and a control computer with tailor-made software developed for monitoring and data interpretation and algorithms for point cloud processing and deformation analysis. The system operates fully automatically and allows permanent monitoring of objects even for longer periods of time. The TLS sensor is remotely controlled via LAN or WLAN hence it is possible to configure the system via the internet. Data processing and report generation are automated and information is accessible via LAN/WLAN/Internet. The system is able to produce reports and send alarm messages for critical object deformations via SMS and/or email. The system was tested on a deformation façade study and the results were verified by a commercial monitoring system (Leica GeoMoS). A comparative analysis of results from the TLS monitoring system and the geodetic system showed that object movements of 1mm or more can be detected by evaluating the area of interest. The detection of a 3D deformation planar area comparison succeeds with a resolution that is within the range of 1 to 2mm at an object distance of approximately 20m. However, certain requirements needed for a geodetic monitoring system such as detection of network stability and the stability of control points are yet to be satisfied by the system and so external measurements taken with total stations are utilised.

Many authors have applied TLS for the detection of deformations in controlled environments, apart from the case studies described above. For instance in Park *et al.* (2007) it is stated that 3D coordinates of a target structure acquired using TLS can have maximum errors of about 10mm and so a displacement measurement model is presented to improve the accuracy of the measurement and tested experimentally on a supported steel beam. Measurements were made using three different techniques: linear variable displacement transducers (LVDTs), electric strain gages and a long gage fiber optic sensor. The maximum deflections estimated by the TLS model were less than 1mm and within 1.6% of those measured directly by LVDT. It is also stated that the proposed TLS method allows measurement of the entire building's or bridge's deformed shape and thus having a realistic solution for monitoring structures at both structure and member level. Gordon *et al.* (2003)

present an investigation designed to explore the sensitivity of TLS systems for structural deformation monitoring tasks. Two experiments were performed involving controlled load testing of structures. Induced deformation was at the millimetre level and up to several centimetres. Close-range photogrammetry and contact sensors were used to benchmark test the laser scanner data. In each experiment, it was shown that the TLS systems were able to measure vertical deflection at six to 12 times better than their advertised single point precision. In one test, a TLS (single point precision of ±6mm) achieved an accuracy of ±0.5mm (RMS).

4.1 Deformation analysis

Unlike change detection, during deformation analysis, a more detailed investigation is carried out. However, the deformations that are to be found can be the order of magnitude of the point accuracy, but also in the same order as the noise. For instance, the registration of the point clouds influences the accuracy of the point clouds and therefore the possibility to detect deformations (Lindenbergh, 2013). The sub-sections below describe three deformation methods.

4.1.1 Point to point based deformations

Structural deformation monitoring is typically undertaken with point-wise surveying techniques (Gordon *et al.,* 2003; Lovas *et al.,* 2008) as earlier mentioned. With TLS, it is uncertain that the exact same point is sampled at two different epochs and deformation analysis based on points is impossible due to the inability to reposition the scanner in the same location and issues of the laser beam-width (Alba *et al*., 2006; Lichti and Gordon, 2004). Furthermore, the point density on an object can vary as it is scanned from multiple standpoints. A direct point to point comparison is therefore not favourable. However, it can be argued that depending on how the study is designed in terms of data collection and processing, point to point based deformation analysis is possible and capable of achieving the objectives of a study. For instance, Little (2006) used a point-wise comparison to monitor mining excavation. Two laser scanners were permanently installed on the sides of the mining pit. On the slope that was investigated, a regular grid with intervals of 5m was created. Only those points were measured, twice a day. A point-wise comparison was carried out to monitor the volume changes. Tsakiri *et al.* (2005) used retro-reflective targets that were placed on the object. These targets were scanned during multiple epochs and for each target the centre was calculated. Results showed that deformations below 0.5mm can be detected using TLS and targets.

4.1.2 Point to surface based deformations

One of the main advantages of laser scanning is that it provides dense 3D information of the surface of an object. For the point to surface method, the high point density of TLS is useful. One of the point clouds is represented by a surface and for a point in the second point cloud the distance to the surface is calculated (Lague *et al.,* 2013). There are different ways of surface representation such as tessellations where a surface is represented by means of a mesh for instance. Many reconstruction programs perform triangulation, which converts the given set of points into a consistent polygonal model (mesh) (Tsakiri *et al.,* 2006). The point cloud can also be fitted using functions or surfaces such as planes, spheres, cylinders and the Non-Uniform B-Splines (NURBS) (e.g. Vezocnik *et al.,* 2009; Wang, 2013; Gonzalez Aguilera *et al.,* 2008).

The point to surface method is exemplified in van Gosliga *et al.* (2006), where a procedure was developed to detect deformations of a bored tunnel as highlighted in the case studies above. The tunnel model was fitted to a point cloud consisting of several registered TLS scans using a linearized iterative least squares approach. The point clouds were then converted to a local spherical coordinate system, using the estimated cylinder so that deformations were perpendicular to the tunnel axis. All the data points were interpolated to a regular grid, assuming that the tunnel was locally flat. Between the two acquisitions, artificial deformations were placed in the tunnel. The difference in the range for a grid point was tested on deformation. The results that were achieved from the study demonstrated the potential of using TLS data for deformation analysis as the method that was employed was capable of detecting deformations.

4.1.3 Surface to surface based deformations

This method is exemplified in Lindenbergh and Pfeifer (2005) where the lock (gate) was scanned twice from a fixed position and the first attempt at data processing involved a direct point to point comparison of the observed points, since the scans were acquired from the same fixed position. However, range differences were observed on certain parts of the lock between the two scans and background shifts between connected surfaces hit by the laser signal. The explanation was attributed to systematic errors or change of coordinate systems between the two scans and strong wind. The next step involved segmentation of the point cloud into homogeneous areas. For each of the segments, a plane was fitted and comparisons were made between the two epochs. At this stage, the method became point to surface, as for every point the residual to the plane was investigated. The residuals showed different deformation regimes for the inner and outer areas and so the use of one plane for the entire segment was not appropriate. Therefore, the area of each segment was divided into grid cells of equal size (5×5cm) and for each cell, a plane was fitted to all the points contained therein. The plane parameters and their covariance matrices were then used to perform deformation analysis, resulting in a surface to surface method. The method employed was capable of detecting deformation of the order of 9mm with a certainty of 95% for areas of size 5×5cm. The optimal cell size had not been investigated in the study and it remained as a subject of future research.

4.2 Summary

Deformation monitoring using TLS as discussed above has been applied in the monitoring of several structures such as dams for instance (Alba *et al.,* 2006; Gonzalez Aguilera *et al.,* 2008), tunnels (van Gosliga *et al.,* 2006; Li *et al.,* 2012; Gikas, 2012; Han *et al.,* 2013), viaducts and bridges (Zogg and Ingensand, 2008; Lovas *et al.,* 2008), buildings and towers (Pesci *et al.,* 2013; Schneider 2006), concrete and timber beams (Gordon *et al.,* 2003) and the monitoring of a pipeline as described in Vezocnik *et al.* (2009). TLS has also been applied with success in land deformation monitoring (Wujanz *et al.,* 2013; Teza *et al.,* 2007) and rock slopes as described in Abellan *et al.* (2009). Some findings from the application of TLS in tunnel construction surveys are worth mentioning as observed from literature. According to Gikas (2012) modern TLS systems are able to be used in the underground environments and capable of coping with demanding operating conditions (such as dust and damp) and they can operate in darkness as they are active sensors. However, there are some challenges of TLS application in tunnelling surveys. For instance the point cloud produced by TLS might not fully sample the scanning surface due to shadows relating to the relative geometry (viewing angles) between the instrument and the scanned section. In addition, the presence of reflective objects (e.g. equipment and water) in the field of view of the instrument can affect the recognition of targets. Figure 1 highlights the factors that affect TLS data quality in tunnel construction surveys.
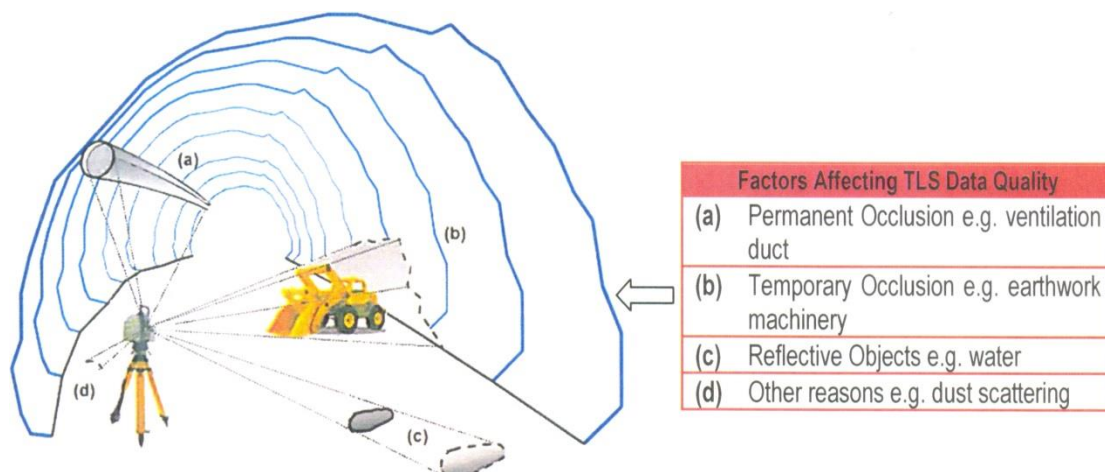

Figure 1: Factors Affecting TLS Data Quality in Tunnel Construction Surveys (Source: Gikas, 2012)

In general, as stated in Monserrat and Crosetto (2008), the exploitation of the high data redundancy provided by TLS is key to achieving good deformation measurement performance with TLS data and often requires the development of ad hoc tools and techniques for processing the data. The case studies reviewed show different ways of processing the acquired TLS point cloud for deformation analysis with the techniques involving: deformation measurement via point cloud registration algorithms, modelling the point cloud via triangulation for instance and performing distance comparisons between them, 3D surface modelling and conducting deformation analysis via cross sections of the model, deformable object shape modelling and reduction to single representation points for deformation analysis. The accuracies achieved in the studies reviewed range from centimetre to millimetre depending on the scanner used and calibration, measurement set-up, environmental conditions, level of registration and/or georeferencing error and the method of point cloud data processing employed for deformation analysis. Furthermore, Alba *et al.* (2006) state that the stability of the reference frame is cardinal in order to separate the displacements from the noise produced by errors within the georeferencing process.

Deformation analysis of TLS data involving both area-wise and a discrete approach where artificial targets are used have been employed in the reviewed case studies. The advantage of area-wise deformation analysis is that the whole deformable object is analysed whereas the discrete approach is only for specific areas of the deformable object (Mechelke *et al.*, 2013). However, derived single representative points of the object after fitting the point cloud have also been used for deformation analysis as in Vezocnik *et al.* (2009). Point to point deformation analysis using artificial target such as spheres and retro-reflective targets placed on a deformable object and scanned at different epochs (Tsakiri *et al.*, 2002; Zogg and Ingensand, 2008) have also been reported to have achieved better results at millimetre accuracy. This millimetre accuracy level is possible to achieve because the calculation of the centre of sphere targets for instance is based on adjustment theory (Schafer *et al.*, 2004) and a typical example is depicted in Schneider (2006) where the scanner software was able to measure the target centre with millimetre accuracy by applying an intensity-weighted centroid operator on multiple points covering the target.

The Point to surface method for deformation analysis has in essence been applied as a change detection approach like the cloud to mesh described in (Lague *et al.*, 2013) and also as a deformation monitoring technique. A distance measurement is computed from the point cloud to the surface in investigating the change between epochs. Actually, Barnhart and Crosby (2013) undertook a study comparing two change detection techniques in the natural environment, namely: the cloud to mesh and the Multiscale Model to Model Cloud Comparison (M3C2). It was shown that the cloud to mesh technique provides a good approximation of surface change, yet does not take into account the local orientation of the surfaces represented by the point clouds. For the M3C2 techniques, it was found that it provides a better accounting of the sources of uncertainty in TLS change detection because it considers the uncertainty due to surface roughness and scan registration. However, the cloud to mesh method has been used with success to investigate structural and surface deformation (Monserrat and Crosetto, 2008). Other than the example given by van Gosliga *et al.* (2006) for the point to surface deformation analysis approach, Teza *et al.* (2007) applied the point to surface approach in calculation of a displacement field via the developed Piecewise Alignment Method.

The surface to surface method has also been applied in deformation analysis as exemplified in Lindenbergh and Pfeifer (2005) to detect deformations on a lock (gate). The attempts to apply a point to point deformation analysis in this study proved futile and so a surface to surface method had to be applied. Deformation analysis based on the direct comparison of acquired points is not possible because even when the scanner is at the same position in the different epochs, the same point cannot be scanned (Walton *et al.*, 2014) due to for instance non-uniqueness of reflective points between epochs, changes in environmental conditions or even multipath.

An automated TLS based deformation monitoring system as presented in Mechelke *et al.* (2013) though with some improvements needed on the system is one of a kind and clear testimony that the technology has matured. This is so because known automated geodetic monitoring systems that have been developed involve robotic total stations supplemented by GNSS and software capable of providing fully automated data gathering, processing, alarming and graphical display of displacements and a typical case in point is the Diamond Valley Lake project in California (Chrzanowski *et al.,* 2011).

5.0 Registration and Georeferencing in Terrestrial Laser Scanning

Several efforts and methods have been developed in the past for registering 3D point clouds especially in the field of Computer Vision (dos Santos *et al.,* 2013; Gruen and Akca, 2005). The registration problem has primarily been approached by a landmark registration method called the Iterative Closest Point (ICP) algorithm developed by Besl and McKay (1992). The original version of ICP is based on the search of pairs of nearest points in the two sets and estimating the rigid transformation which aligns them. Then, the rigid transformation is applied to the points of one set and the procedure is iterated until convergence. The ICP assumes that one point set is a subset of the other. When this assumption is not valid, false matches are created which negatively influences the convergence of the ICP to the correct solution (Gruen and Akca, 2005). The ICP is a fine registration method that requires initial coarse registration of data and several versions and improvements of the ICP method have been made by different researchers (Chen and Medioni, 1992; Zhang, 1994; Masuda and Yokoya, 1995; Li and Griffiths, 2000; Rusinkiewicz and Levoy, 2001; Okatani and Deguchi, 2002; Segal *et al.,* 2009; Du *et al.*, 2010). Additionally, other researchers have also developed other notable variants of the ICP such as the Iterative Closest Patch (ICPatch) where points in one scan and triangular irregular network patches in another scan serve as the geometric primitives (Habib *et al.,* 2010) and the Iterative Closest Projected Point (ICPP) which focuses on minimising the distance between a point in one scan and its projection on the plane defined by the closest three points in the other scan (Al-Durgham *et al.,* 2011).

The Least Squares 3D Surface Matching (LS3D) is another registration method proposed by Gruen and Akca (2005) which achieves a solution by minimisation of the sum of squares of the spatial (Euclidean) distance between the different datasets and the need of a very good initial value for the registration is a must. Furthermore, Akca (2007) developed an extension to the basic LS3D algorithm, which can simultaneously match surface geometry and its attribute information, e.g. intensity, colour, etc. under a combined estimation model. Conventionally, registration in TLS has mainly been through indirect registration which implies making use of target features (artificial or natural) in the scene itself to align datasets (Lerma *et al.,* 2008; Wujanz *et al.,* 2013). To perform an indirect registration at least three non-collinear target correspondences between two scans are needed. However, it is always better to have more than three so that errors can be minimized by performing a least-squares optimization. If georeferencing is required, the targets themselves should be recorded and transformed into a known coordinate system using recognised surveying methods (Lerma *et al.,* 2008). In principle, georeferencing in TLS can either be through indirect or direct methods (Reshetyuk, 2009) and the section below reviews some of the notable case studies on the methods of registering and georeferencing TLS data.

In Grant *et al.* (2013) a comparative study of the ICP and the Point-to-Plane (P2P) registration algorithms was carried out. The study was aimed at investigating the question of pairwise registration consistency and the following has been reported: considering two scans (A and B), the question to be answered was, will the registration parameters be the same if scan A was registered to scan B and vice versa? The P2P algorithm was found to be very consistent and the differences in registration accuracy between the forward and backward modes were negligible when using the P2P algorithm (mean difference of 0.03mm). However, the ICP had a mean difference of 4.26mm. Each scan was also transformed by the forward and backward parameters of the two algorithms and the misclosure computed. The mean misclosure for the P2P algorithm was 0.80mm whilst that for

the ICP algorithm was 5.39mm. Furthermore, Grant *et al.* (2012) state that the P2P registration approach was tested on both simulated and real TLS data and that experimental results showed it to be four times more accurate than the registration approach of Chen and Medioni (1992).

Al-Manasir and Fraser (2006) describe a registration method for TLS data using photogrammetric orientation of images from a camera attached to the laser scanner where digital images captured have been used for registering adjacent laser scans. The photogrammetric network is established and solved using least squares to enable the registration of overlapping laser scanning data. From the tests carried out with the Image Based Registration (IBR) method the following accuracies are reported: In the first test application involving a laboratory test field, the accuracy attained in the registered point cloud was 3mm. In the second test survey, a practical scenario involving manual image measurement to half-pixel accuracy, the 3D model formed using the method was found to be in overall alignment with that obtained via an ICP registration to a root mean square error of 2.7mm. In the third, more complex test application it was demonstrated that the IBR is well suited to providing point cloud registration in situations where there is limited overlap between adjacent TLS point clouds. An automatic registration method of laser scanner data is also presented in Al-Manasir (2013) where an iterative similarity registration method has been used to register TLS data. A linear form of the 3D similarity transformation is used to register TLS data without the need for markers in the scene to aid the registration. Two experiments of the method were conducted, the first one was a laboratory test and the second one was a practical test involving the scanning and registration of a heritage cottage. In the first test, the method's attained registration accuracy as assessed against true coordinate values was 4mm. In the second test, the 3D model formed via the method was found to be in overall alignment with that obtained via an ICP registration to an RMSE of 4.2mm. Even in a case where 3 co-planner points are used, the method can still obtain a solution as compared with the closed form 3D similarity transformations.

Dold and Brenner (2006) present a registration method of TLS Data using planar patches and image data without need for targets. A search technique is used to find corresponding patches in two overlapping scans. The matching of correspondent patches is supported by geometrical features derived from the TLS data. The patches are estimated fully automatically using a region growing algorithm, which was adapted to handle 3D TLS data. Image data from the camera attached to the scanner is used to improve the registration process. Assuming that the calibration parameters of the scanner and camera system are known, the extracted planar patches can be textured automatically. The correlation coefficient between two corresponding textured planar patches is calculated and the result is used to verify the correspondence of the patches. Furthermore, the uncertain translation component of the transformation can be determined by shifting and correlating the texture patches until they fit best hence improving the registration. The method worked well and it is an improvement to some existing manual and semi-automated registration methods. Zhang *et al.* (2012) also describe a robust algorithm for the registration of building point clouds based on the planar features segmented from TLS data. The first part of the procedure involves obtaining normal vectors of the planes that are fitted from the segmented point clouds in the overlapping areas in order to generate completed 3D models and then a mathematical model of registration is employed by using the character of the Rodriguez Matrix. The algorithm does not involve iterative calculations and initial values as in the ICP method. In one of the experiments the accuracy of the registration method was analysed and compared to the ICP method where four spheres were fitted in both stations and their center coordinates were used as checkpoints. The postfit errors for the checkpoints ranged from -2.53 to 0.55cm, compared with -3.14 to 0.13cm using the ICP method. The root mean square values ranged from 0.30 to 2.23cm, compared with 0.32 to 2.74cm using the ICP method.

Al-Durgham *et al.* (2013) present an approach for the registration of TLS scans by an automatic matching method that uses 3D linear features. Linear features were extracted from the scans and they were used for the estimation of the transformation parameters. Conjugate linear features were selected based on random selection of line pairs that have similar spatial separation and angular

deviation values. The registration workflow simulates the well-known Random Sample Consensus method (RANSAC) for determining the registration parameters, whereas the Iterative Closest Projected Point (ICPP) is utilized to determine the most probable solution of the transformation parameters from several solutions. The derived transformation parameters using linear features provided very good approximation values for the ICPP procedure. The synergistic integration of two different registration methodologies (i.e., linear features and ICPP) helps in overcoming the drawbacks of each method. The approach provided a good solution to automate the registration of TLS scans. dos Santos *et al.* (2013) describe indirect georeferencing of TLS data using control lines and listed below are the procedural steps for the extraction of control lines and corresponding TLS lines and their utilisation for estimating the parameters of the transformation function.

   i.   Appropriate control lines in the ground reference coordinate system are measured. The control lines can also be measured using field survey methods for better accuracy or they can be derived from a map or images if accuracy requirements are not stringent.
   ii. Corresponding lines in the point cloud are measured. Each line is extracted by segmenting its adjacent surfaces, thus fitting planes to the surfaces and intersecting the planes.
   iii. Pairs of corresponding lines are used in a least squares adjustment procedure to estimate the georeferencing parameters which are used to georeference the point cloud.

The above three step georeferencing method was tested using both simulated and real data, and the advantages of this new approach were compared with conventional surveying methods. The experiments with the real data for instance indicated that georeferencing accuracies of the order of a few millimetres can be achieved by using straight lines in the new method. All of the residual distributions were centred approximately at zero, implying that the model is appropriate and that the overall adjustment estimation is reliable (dos Santos *et al.,* 2013).

Yang and Zang (2014) describe an automated method of registering TLS data of complex freeform objects using curves as matching primitives to overcome the limitations of registration methods that use points, lines or patches as primitives as they have challenges in registering freeform objects. Firstly, the method clusters visually prominent points selected according to their associated geometric curvatures so as to extract crest lines which describe the shape characteristics of point clouds and then use them as invariant features for registration primitives. Secondly, a deformation energy model is constructed describing the shape characteristics of the extracted crest lines and to select the correct matching curve pairs, resulting in good initial orientation parameters between scans. Finally, fine registration was achieved using the ICP algorithm. The accuracy of the method was assessed through experiments and an accurate registration solution was achieved for complex scenes. Bae and Lichti (2004) present a TLS registration method to find the correspondence of two point clouds using geometric primitives and a local search algorithm based on the understanding that geometric primitives, such as surface normal vector, curvature and the change of curvature provide useful information to recover the correspondence of two point clouds. The method was evaluated with a simulated point cloud with various levels of noise and two real point clouds captured with two different laser scanners. The registration errors for real point cloud were the order of centimetre and that of a simulated dataset were similar with the standard deviations of zero-mean Gaussian noise. In Bae and Lichti (2008) an automated point cloud registration method called Geometric Primitive ICP with the RANSAC (Random Sample Consensus) is presented. The Cramer–Rao lower bound of registration error was derived by considering position uncertainty. Then a RANSAC method was used to remove outliers based on position uncertainty. It was demonstrated that the method improved the precision of the estimated relative transformation parameters as much as a factor of 5 hence providing an opportunity to utilise the method in applications such as deformation monitoring.

Han (2010) presents a novel approach for the registration of TLS point clouds from multiple scanning stations. The approach uses hybrid geometric features involving points, lines, planes and groups of points to solve the similarity transformation parameters between two TLS datasets. The proposed solution is expressed in a closed form meaning that an initial alignment or an iterative

computation is not required. A real case study was undertaken to test the approach where a concrete structure was scanned from two stations at a distance of about 10m from the object with an average point resolution of 2cm. Three checkpoints were also scanned from the two stations to only provide quality check for the approach. In order to construct the relative geometric matrix required to estimate the rotation matrix using the proposed approach, three groups of points representing the conjugate features in the two datasets were selected. The post fitting errors for the checkpoints ranged from −3.1 to 3.3cm with RMS values ranging from 2.6 to 2.9cm in each direction. The accuracy level was taken to be of acceptable magnitude considering the 2cm resolution of the original point clouds and that the method is efficient and reliable.

The direct method of georeferencing uses additional sensors such as navigation sensors, total stations or the inclination sensors to estimate directly the laser scanner's position and orientation. The accuracy of the method depends on the quality of the derived scanner position and the orientation information of the additional sensor (Paffenholz and Kutterer, 2008). Direct georeferencing for TLS using GNSS is advantageous in several ways such as existing survey control may not be needed if determination of the scanner's position and backsight target is performed with GNSS, avoidance of errors due to centering of the scanner and backsight target (Reshetyuk, 2009) and applicable on sites inaccessible for the installation of targets (Mohammed and Wilkinson (2009). In a similar vein Lerma *et al.* (2008) state that direct georeferencing technique in TLS using GNSS reduces the number of targets to be placed and therefore avoids the quite demanding requirements on the target configuration. When georeferencing is required, the measured reflector position can be transformed into a specific known coordinate system using general surveying techniques. With reference to Figure 2 below, a TLS generally measures the points of the scanned object in three dimensions (Staiger, 2003) and the three dimensional Cartesian coordinates for each measured point are derived from the basic measurements of range, ρ, horizontal direction, θ, and elevation (vertical) angle, α. These coordinates are referenced to the instrument's internally defined system, (x, y, z), which makes georeferencing into an external coordinate system, (X, Y, Z), necessary. Figure 2 also illustrates the observables and related coordinate systems in the context of the direct scanner georeferencing (Lichti and Gordon, 2004).
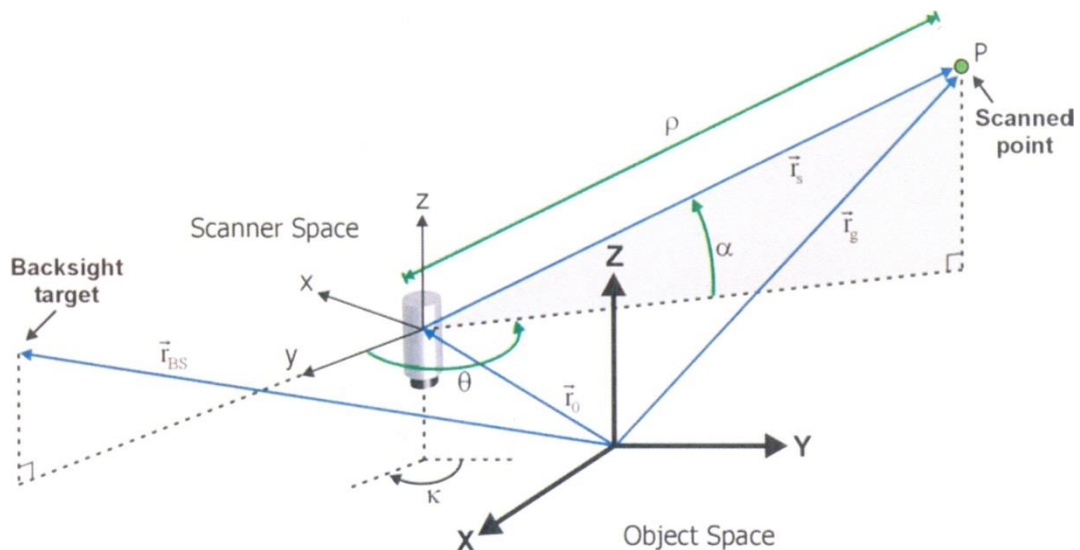

Figure 2: TLS observables and direct georeferencing (Source: Lichti and Gordon, 2004)

Paffenholz and Kutterer (2008) describe an adapted sensor-driven approach for TLS direct georeferencing using two GPS antennas mounted on top of the scanner at a distance of about 0.6m from each other. The method dealt with the estimation of the sensor position with GNSS antennas installed on the scanner. The advantage of the method was the constant use of the rotation of the scanner with the combination of kinematic GNSS measurements. The main issues to solve with the approach were the problem of time synchronization of the scanner data and the position and the

other issue to solve was the calculation of an azimuth for each scan line in the 3D laser scan from the GNSS trajectory of the sensor. The method achieved a metric uncertainty of about 1cm for the azimuth calculation on a distance of 30m. However, Reshetyuk (2009) states that the applicability of this approach is limited by the accuracy of the azimuth determination. The approach would work only for phase difference scanners with medium distances up to 30m because for larger distances between 30 and 53m, the metric uncertainty raised to the order of 10cm. The attainable accuracy of the azimuth determination is limited by the distance between GNSS antennas mounted on the scanner. In addition, mounting two GNSS antennas onto the scanner may need a complicated and heavy adapter which can be beyond the weight that a scanner can sustain compared to mounting only one. Therefore, mounting of two GNSS antennas may not be possible for all scanner models and millimetre accuracies may not be achieved.

Reshetyuk (2009) describes a method for directly georeferencing TLS scan using GNSS and the assessment of the coordinate accuracy in the point cloud using with the method. The scanner position was determined through Real time kinematic GNSS technique and the back-sight target position was determined by processing static GNSS measurements. The results of the coordinate accuracy showed that it is possible to achieve accuracy better that 1cm in both plane and height in the point cloud at a distance of up to about 70cm to the object. Mohammed and Wilkinson (2009) present a system consisting of a dual GNSS antenna apparatus to the scanner setup. The research work describes a new method for determining the 3D absolute orientation of TLS point cloud using GNSS measurements from two antennas firmly mounted on the optical head of a stationary TLS system. In the study, the general case is derived where the orientation angles are not small and that the case completes the theory of stationary TLS direct georeferencing. Simulation and real world field experimentation of the prototype implementation suggested a precision of about 0.05 degrees (~1 milli-radian) for the three orientation angles.

The coordinate transformation between two TLS point clouds can be considered as a 3-D rigid body transformation decomposed into a rotation and a translation (Tournas and Tsakiri, 2008). However, Scaioni (2012) looked at two main considerations on the estimation of a rigid-body transformation which is a basis of registration and georeferencing in TLS. The first issue concerned the analysis of the stochastic model of Least Squares estimation of the transformation and states that in practice, the control points used for parameter estimation are considered as being precise and in order to assess this, two different approaches for weighting observations in laser scan and ground control points were proposed and evaluated through a set of Monte Carlo simulations. The second issue was reliability analysis and it was proposed that a further chance to increase the local redundancy of laser scan observations is to combine the adjustment for computing georeferencing parameters to the one of the geodetic network for the determination of GCP coordinates. The results showed that the two issues investigated are worth considering especially in high-precision applications such as deformation monitoring.

5.1 Evaluation of the Registration and Georeferencing Techniques

It is evident from the above discussion that a critical component within the process chain of change detection and deformation monitoring is the transformation of captured TLS point clouds into a reference respectively superior coordinate system. This step has mostly been carried out using artificial targets (Wujanz *et al.,* 2013). In addition, a laser scanner is a line of sight instrument and in many cases the object has to be scanned from different viewpoints in order to completely reconstruct it. Because each scan has its own local coordinate system, all the local point clouds must be transformed into a common coordinate system via registration (Gruen and Akca, 2005). The need for accurate registration and georeferencing of TLS data in change detection and deformation monitoring studies has been emphasised by many researchers. For instance, Monserrat and Crosetto (2008) state that an accurate registration is important in order to avoid systematic errors in the estimated deformation parameters. Lague *et al.* (2013) have pointed out registration uncertainty in TLS as one of the main sources of uncertainty in point cloud comparison for change detection. In deformation monitoring applications the orientation of TLS measurement data is a

crucial point (Schneider, 2006) and the dominance of the georeferencing error should be prevented (Teza *et al.,* 2007; Lindenbergh, 2013). There is need to improve the accuracy of scan georeferencing, which depends on the geometric distribution of ground control points as well as on the accuracy of their measurement. The measurement of targets is an aspect which should be investigated again, because probably it depends on the incidence angle between laser beam and target surface. However, the strategy of increasing the number of targets to improve the reliability of georeferencing could be a good operational solution (Alba *et al.,* 2006).

In Alba *et al.* (2007), a review and comparison of three existing georeferencing techniques for TLS data was carried out involving a laboratory test and a real case study. The classical GCPs-based georeferencing (indirect method) was conducted; direct georeferencing was performed by using coordinates of each TLS standpoint obtained from the measurements of a geodetic network using a total station. An option was also tested where TLS was used to measure the standpoints of a geodetic network without using the total station measurements. The laser scanner was put on each vertex of the network, but this time considered with unknown coordinates, levelled and oriented azimutally. From each standpoint, range, horizontal and vertical angles towards the preceding and the next vertex of the traverse were measured. Two cylindrical retro-reflective targets were placed on a tripod over the monument of the network. The resulting coordinates of the close traverse's vertices were calculated by least squares adjustment. The residuals on independent check points as shown in Table 1 were not better than those based on direct georeferencing with total station measurements. The surface matching method was also tested and analysed where the ICP-based alignment was applied to the whole dataset. The target coordinates in every scan were compared to GCPs determined with total station. For all methods, the indirect method had better results (Table 1).

Table 1: Results of Georeferencing Methods based on Independent Check Points

Rejection (cm)	Indirect		Direct with Total Station		Direct without Total Station		Surface Matching	
	X, Y	Z	X, Y	Z	X, Y	Z	X, Y	Z
Sqm	0.5	0.3	0.9	1.6	1.1	1.5	0.9	1.1
Max	1.2	0.5	3.2	-4.0	3.7	3.6	2.6	3.9
Media	0.0	0.0	-0.3	-0.1	1.0	0.5	0.1	1.4
RMS	0.5	0.3	0.9	1.6	1.5	1.6	0.9	1.8

Source: Alba *et al.* (2007)

With reference to Table 1, the accuracies obtained from both methods based on direct georeferencing were not better than the other approaches (Alba *et al.,* 2007). Indirect georeferencing using targets is capable of achieving millimetre accuracy and is the most accurate compared to direct georeferencing (Schuhmacher and Böhm, 2005) and this is proved in the accuracy ranges obtained with even the above discussed GNSS direct georeferencing methods (Paffenholz and Kutterer, 2008; Reshetyuk, 2009). The method of georeferencing TLS data using control lines is also a good method which was able to achieve millimetre accuracy. Linear features were used to georeference TLS data, which is different from previous works in which lines have mainly been used for the registration of TLS datasets. A point worth emphasising in this method is that strong geometric distribution of control lines is needed to produce better results in general (dos Santos *et al.,* 2013).

As already mentioned, surface based algorithms such as the ICP or algorithms based on discrete points have been used to register TLS point clouds (Schneider, 2006). The popular ICP registration method has also undergone several improvements as discussed. However, other registration methods have been developed with some advantages over the ICP in some situations. A case in point is the Image Based Registration (IBR) method which provides a fast, robust alternative to the ICP algorithm in situations where special targets such as retro-reflective targets are employed, since the IBR can be implemented as a fully automatic process but in situations where no targeted tie

points are available, conjugate points have to be found manually (Al-Manasir and Fraser, 2006). Furthermore in Al-Manasir and Fraser (2006) the IBR method demonstrated that it is well suited to providing point cloud registration in situations where there is limited overlap between adjacent TLS point clouds overcoming the limitation of the Least Squares 3D surface matching in Gruen and Akca (2005) and that for TLS instruments with integrated digital cameras, the IBR method offers a viable approach to solving the point cloud registration problem.

Dalley and Flynn (2002) undertook a study on several popular techniques for performing fine registration of partially overlapping 2.5D range image pairs, with a focus on model building and they qualitatively evaluated the output of several ICP variants on real-world data. The pixel to point correspondence and the computation of the transformation parameters were integrated in an iterative process. In Han (2010) the registration solution is expressed in a closed form implying that an initial alignment or an iterative computation is not required and this solves the problem faced by iterative approaches where they become inefficient in cases of non-availability of good initial values or where the computation involves a large dataset. However, Al-Manasir (2013) presents an iterative similarity registration method which is fully automatic without the need to use markers and capable of registering TLS data with millimetre accuracy as mentioned above. Though iterative, the method was able provide a fast and reliable solution with only 5 iterations to register two scans in a field test compared to the ICP algorithm which had 130 iterations to achieve a four-scan registration to the same accuracy as the method.

Although indirect georeferencing methods are the most accurate, cases where a medium accuracy is enough (i.e. at 2-3cm level), direct methods are really operational (Alba *et. al.,* 2007) and with GNSS direct georeferencing for instance, there is no need to create a survey network which leads to saving field-work time and project efficiency (Mohammed and Wilkinson, 2009; Lerma *et al.,* 2008). Direct methods can be applied regardless of the morphology of the surveyed object because they do not require any overlapping between scans or rich textures to successfully apply surface matching techniques. In principle, the selection of the georeferencing method to adopt depends on the object shape and the required accuracy of measurements (Alba *et. al.,* 2007) among other factors such as technical, economical and operational issues. However, Lindenbergh and Pietrzyk (2015) state that regardless of the method (indirect or direct) used to register or georeference the laser scanning point cloud, the processes of registration or georeferencing add to the error budget in a particular way and they have to be kept to a minimum as much as possible.

6.0 Deformation Analysis: A Proposed Three-Stage Process Model

Elaborated below is a proposed three-stage process model for deformation analysis (Figure 3) conceptualised from the literature reviewed. The proposed deformation analysis model consists of the Multiscale Model to Model Cloud Comparison (M3C2) technique, the Piecewise Alignment Method and the Block to Point Method which are explained in detail in the sub-sections below. The aim is to develop a stand-alone modelling system with capabilities for change detection and deformation analysis. The motivation being that it was observed from the reviewed material that change detection and deformation analysis are mostly conducted separately even in cases where both are needed to make an informed decision. The proposed model with its composition of techniques has not yet been used in structural deformation monitoring. The synergistic integration of the techniques as in the proposed model allows for the techniques to complement each other and addresses their respective drawbacks instead of applying them in a disjointed manner. The integration of the techniques in the proposed three-stage model comes with several advantages and the techniques have been proven to have worked as mentioned in section 6.4.
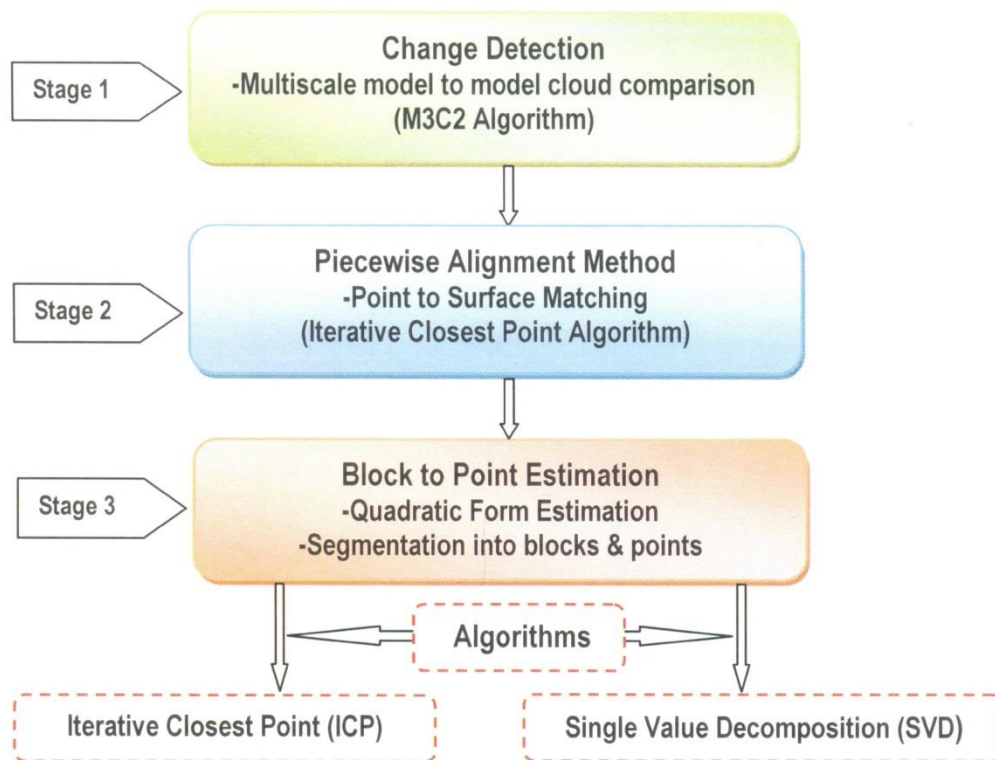
Figure 3: A three-stage process model for deformation analysis

6.1 Multiscale Model to Model Cloud Comparison (M3C2) algorithm

The M3C2 algorithm is a change detection technique which was developed by Lague *et al.* (2013). The M3C2 algorithm can be broken into two steps: point normal estimation and difference computation (Barnhart and Crosby, 2013). Assuming that the two clouds correspond to successive surveys, the first one will be called the reference cloud, and the second one the compared cloud. A set of calculation "core" points is used for which one distance and confidence interval is calculated (Lague *et al.,* 2013). The point clouds themselves may also be used directly treating each point as a core point if a greater spatial resolution of normal calculation is desired (Barnhart and Crosby, 2013). The core points are in essence a sub-sampled version of the reference cloud which can be obtained by random sampling or octree method in an open source software like Cloud compare but the original data is still used in all the calculations. The advantage of using core points is that they improve the operational efficiency by speeding up the calculations because less data is used while maintaining a good accuracy (Lague *et al*., 2013). The M3C2 algorithm has been proved to be a robust change detection technique compared to several other existing techniques as it addresses their limitations as mentioned in section 3.0. For instance, Barnhart and Crosby (2013) found that the M3C2 algorithm provides a better accounting of the sources of uncertainty in TLS change detection than the cloud to mesh technique, because it considers the uncertainty due to surface roughness and scan registration.

6.2 Piecewise Alignment Method

According to Teza *et al.* (2007) the measurement of displacements of an object being monitored using TLS is not direct, but requires comparison between models. The problem of the determination of a deformation field using 3D data has been studied in various disciplines and one notable example is that of Monserrat and Crosetto, (2008) were least squares 3D surface matching (LS3D) was used to determine deformation measurements. The Piecewise Alignment Method as developed by Teza *et al.* (2007) is based on the Iterative Closest Point (ICP) algorithm for the automatic calculation of a displacement field and it involves the following steps:

  i.   Generation of the reference model.
  ii. Preparation of the second multi-temporal data set i.e. data filtering and georeferencing. This
       dataset is not to be modelled as the alignment is point-to-surface.

iii.   Subdivision of the second data set in a series of sub-areas via the usage of specifically conceived Matlab functions.

iv.   For each sub-area, automatic importation into PolyWorks, alignment to the reference model, and storage of rototranslation matrices by means of an original macro.

v.   Computation of displacements in Matlab using appropriate equations.

The Piecewise Alignment Method has been demonstrated to be a valid method for the calculation of the displacements (Teza *et al.,* 2007). The method is promising to work well in the proposed three-stage model as the focus is deformation monitoring of structures with surfaces consisting of 3D geometry which is ideal in ensuring convergence to a reliable solution in multi epoch comparisons since the Piecewise Alignment Method is based on the ICP algorithm.

6.3 Block to Point Method

Wang (2013) described the Block to Point Method for fine registration in TLS which aimed at improving the quality of registration and reducing the effect of random and systematic errors between the scans in TLS applications. The method worked successfully and it was proposed to be used for deformation monitoring applications as a subject of future research and not only for fine registration. The method is as presented in Figure 4 with some modifications made so as to adapt it to the proposed three-stage model for deformation analysis.
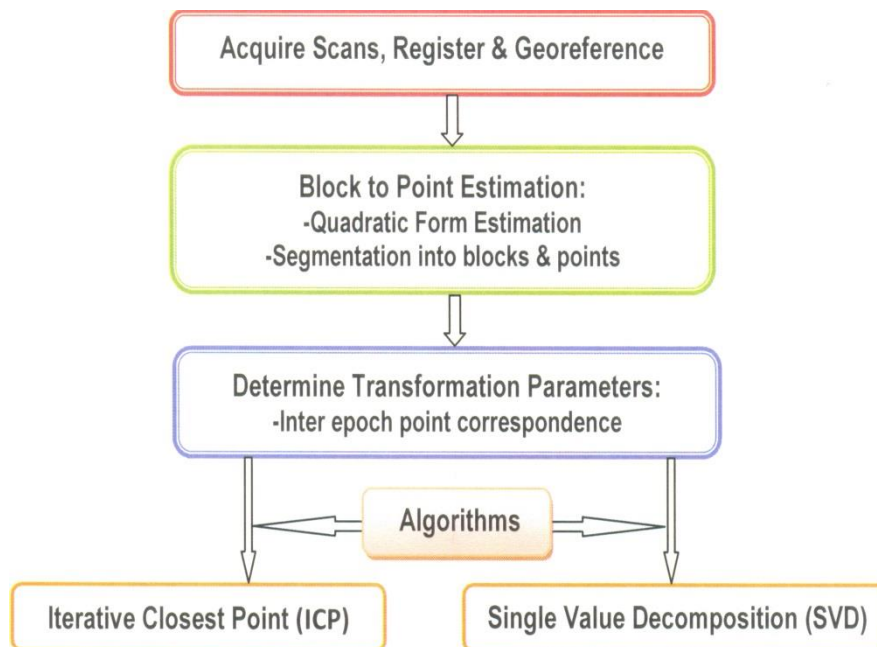

Figure 4: Workflow for Deformation Analysis, Modified from Wang (2013).

With reference to Figure 4 above, the Block to Point Method involves firstly, a TLS survey that is carried out and the scans are registered using homologous points and transformed from the scanner coordinate system to an absolute ground coordinate system through the indirect georeferencing method. Secondly, is the block-to-point estimation which consists of two sub-components i.e. quadratic form estimation and segmentation. The quadratic form estimation is meant to describe the object surface and then segmentation is meant to divide the object surface into small blocks based on point clouds from TLS. The point cloud in each block is then estimated as a representative point. Thirdly, based on the obtained representative points inter epoch transformation parameters of the points are determined by applying the ICP algorithm and the SVD.

6.4 Three-Stage Process Model: Workflow and Implementation

The proposed three-stage model (Figure 3) consists of both change detection and deformation analysis stages. Change detection is the first stage (involving the M3C2 algorithm) and if no change has occurred then there is no need to proceed to deformation analysis stages (involving Piecewise Alignment and Block to point Methods) which aim at quantifying changes at a more detailed level

i.e. small area and even single point locations. The principle guide in the application of the proposed model is the expected signal to noise ratio in the study undertaken. As stated in Lindenbergh and Pietrzyk (2015), if the changes for the object monitored are for instance big and evident, a straight-forward and efficient method should be employed (e.g. M3C2 algorithm). The more involving deformation analysis methods should only be resorted to when there is need for detailed analysis based on initial change detection results or if it is a requirement from the onset of the study to carry out a thorough and detailed investigation.

The proposed three-stage model is a promising tool based on its composition to solve the limitations faced by some techniques such as the DEMs of difference which have limited sensitivity to small deformations and only provide deformation results in one dimension. For instance, concerning change detection, the M3C2 algorithm was adopted in the proposed deformation analysis model because of all change detection techniques reviewed, it combines for the first time three key characteristics: it operates directly on point clouds without gridding, it computes the local distance between two point clouds along the normal surface direction which tracks 3D variation in surface orientation and it estimates for each distance measurement a confidence interval depending on point cloud roughness and registration error (Lague *et al.,* 2013). The M3C2 algorithm is capable of detecting change with millimetre accuracy. The philosophy behind the Piecewise Alignment Method is similar to the cloud to mesh method which has been used with success to investigate structural and surface deformation (Monserrat and Crosetto, 2008). The Piecewise Alignment Method has a further extension to the cloud to mesh method in that it is able to compute a displacement field which is advantageous and vital in the proposed three-stage model for deformation analysis. The initial Block to point method in Wang (2013) was adopted, modified and integrated in the proposed three-stage model for deformation analysis where the estimated representative points could be compared in order to test if the corresponding points have significant variations in different epochs. The Block to Point Method was used with success in the fine registration of TLS data for a dam study. The method comes with advantages such as improvement in the quality of registration, reduction in the effects of random and systematic errors between the scans in TLS applications and capable of achieving millimetre accuracy. The idea is that the proposed three-stage model and the constituent techniques work in one system and not in a disjointed manner. The proposed three-stage model then needs to be tested to monitor structural deformations.

7.0 Conclusion

Metrological monitoring of large structures such as bridges, tunnels, towers or dams is an important subject since such objects might cause an immense damage in case of a malfunction (Schneider, 2006) and the significance of monitoring structures is evident in several studies reviewed in this paper. A review of literature has shown that TLS has increased in use in change detection and deformation monitoring of structures as a surveying technique necessitated by advancements of modern technology. Deformation measurements with TLS are in principle twofold. Firstly, measurements that compare point clouds acquired at different epochs detect change for the measurement period and secondly, measurements that determine the displacement field for the study epochs. Despite the TLS studies that have been undertaken, some issues still need more research such as rigorous and efficient methods of point cloud processing for change detection and deformation analysis, incorporation of measurement geometry in deformation measurements of high-rise structures and modelling the environmental effects on the performance of laser scanning. Furthermore, Scaioni (2012) states that although research has been conducted on modelling systematic errors, automation of TLS registration and point cloud segmentation, less attention has been put on design of data acquisition and quality assessment.

A review of literature has also shown the trends and capabilities of TLS in change detection and deformation monitoring applications of structures. Not only are point cloud data processing techniques being developed, there is also a research direction in the line of an automated TLS-based

geodetic monitoring system as observed in Mechelke *et al.* (2013). TLS well complements traditional geodetic monitoring techniques and cannot replace proven conventional techniques as all the techniques do not compete but support each other. In some cases like the design of a high quality geodetic network for change detection and deformation monitoring, TLS needs the support of other surveying techniques. Furthermore, Vezocnik *et al.* (2009) state that TLS can be considered as a complementary surveying technique which cannot only be combined with other well established high precision surveying techniques but can also contribute to a more complete understanding of deformations. In as much as TLS is capable of acquiring massive point clouds of an object under study, the key point in exploiting the massive point cloud for change detection and deformation monitoring lies in having rigorous methods of point cloud data processing.

It has been observed from the case studies that TLS is capable of detecting deformations within the millimetre range depending on the methodology applied. However, there are instances where other surveying techniques play a critical role in supporting TLS. For example, in Zogg and Ingensand (2008) where in order to detect absolute deformations of the bridge girder, TLS data was transformed into the reference height system defined by precise levelling and in Vezocnik *et al.* (2009) where precise tacheometry and GNSS positioning were used to design and control the stability of the frame for the evaluation of point cloud displacements acquired with TLS. Furthermore, the millimetre accuracies required for deformation monitoring applications using TLS call for a precise instrument, stringent calibration procedures (Tsakiri *et al.,* 2006) accurate point cloud registration and georeferencing and robust methods for deformation analysis as the core issues. Based on the literature review, a three-stage process to deformation analysis is proposed. The proposed model consists of the Multiscale Model to Model Cloud Comparison (M3C2) technique, the piecewise alignment method and the block to point estimation method.

References

Abellan, A., Jaboyedoff, M., Oppikofer, T. and Vilaplana, J. M. 2009. Detection of millimetric deformation using a terrestrial laser scanner: experiment and application to a rockfall event. *Natural Hazards and Earth System Sciences*, 9, pp.365–372.

Abbas, M. A., Setan, H., Majid, Z., Chong, A. K., Lichti, D. D., Idris, K. M. and Ariff, M. F. M. (2013) Self-calibration for accuracy enhancement of hybrid and panoramic scanners. *Proceedings of the Joint International Symposium on Deformation Monitoring*, Nottingham, United Kingdom, September 9-10.

Akca, D. 2007. Matching of 3D surfaces and their intensities. *ISPRS Journal of Photogrammetry and Remote Sensing*. 62(2), pp.112-121.

Alba, M., Fregonese, L., Prandi, F., Scaioni, M. and Valgoi, P. 2006. Structural monitoring of a large dam by terrestrial laser scanning. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Science*, 36(5), pp.6, (on CD-ROM).

Alba, M., Giussani, A., Roncoroni, F. and Scaioni, M. 2007. Review and comparison of techniques for terrestrial 3D-view georeferencing. *Proceedings of the 5th International Symposium on Mobile Mapping Technology*, Padua, Italy, May 29-31.

Al-Durgham, K., Habib, A. and Kwak, E. 2013. RANSAC approach for automated registration of terrestrial laser scans using linear features. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5/W2), pp.13-18.

Al-Durgham, M., Detchev, I. and Habib, A. 2011. Analysis of two triangle-based multi-surface registration algorithms of irregular point clouds. *International Archives of Photogrammetry and Remote Sensing and Spatial Information Science*, 38(5/W12), pp.61-66.

Al-Manasir, K. 2013. A fully automated registration method for laser scanner data. *IET International Radar Conference*, Xi'an, China, April 14-16.

Al-Manasir, K. and Fraser, C. S. 2006. Registration of terrestrial laser scanner data using imagery. *The Photogrammetric Record*, 21(115), pp.255–268.

Bae, K. H. and Lichti, D. D. 2004. Automated registration of unorganized point clouds from terrestrial laser scanners. *International Archives of Photogrammetry and Remote Sensing*, 35(B5), pp.222–227.

Bae, K. H. and Lichti, D. D. 2008. A method for automated registration of unorganized point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing*, 63(1), pp.36–54.

Barnhart, T. B. and Crosby, B. T. 2013. Comparing two methods of surface change detection on an evolving thermokarst using high-temporal-frequency terrestrial laser scanning, Selawik River, Alaska. *Remote Sensing*. 5, pp.2813–2837.

Besl, P. and McKay, N. 1992. A method for registration of 3-D shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 14(2), pp.239–256.

Chen, Y. and Medioni, G. 1992. Object modelling by registration of multiple range images. *Image and Vision Computing*, 10(3), pp.145–155.

Chrzanowski, A., Szostak-Chrzanowski, A. and Steeves, R. 2011. Reliability and efficiency of dam deformation monitoring schemes. *Canadian Dam Association Annual Conference*, Fredericton, NB, Canada, October 15-20.

Dalley, G. and Flynn, P. 2002. Pair-wise range image registration: a case study in outlier classification. *Computer Vision and Image Understanding*, 87(1), pp.104–115.

Dold, C. and Brenner, C. 2006. Registration of terrestrial laser scanning data using planar patches and image data. *International Archives of Photogrammetry and Remote Sensing*, 36(5), pp.78-83.

dos Santos, D. R., Dal Poz, A. P. and Khoshelham, K. 2013. Indirect georeferencing of terrestrial laser scanning data using control lines. *The Photogrammetric Record*, 28(143), pp.276–292.

Du, S. Y., Zheng, N. N., Xiong, L., Ying, S. H. and Xue, J. R. 2010. Scaling iterative closest point algorithm for registration of m–D point sets. *Journal of Visual Communication and Image Representation*, 21(5–6), pp.442–452.

Dunnicliff, J. 1993. *Geotechnical instrumentation for monitoring field performance*. New York, Wiley.

Erol, S., Erol, B, and Ayan, T. 2004. A general review of the deformation monitoring techniques and a case study: analysing deformations using GPS/levelling. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 35(B7), pp.622-627.

Girardeau-Montaut, D., Roux, M., Marc, R. and Thibault, G. 2005. Change detection on points cloud data acquired with a ground laser scanner. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36 (3/W19), pp.30-35.

Gikas, V. 2012. Three-dimensional laser scanning for geometry documentation and construction management of highway tunnels during excavation. *Sensors*, 12, pp.11249-11270.

Gonzales-Aguilera, D., Gomez-Lahoz, J. and Sanchez, J. 2008. A new approach for structural monitoring of large dams with a three-dimensional laser scanner. *Sensors*, 8, pp.5866–5883.

Gordon, S., Lichti, D., Stewart, M. and Franke, J. 2003. Structural deformation measurements using terrestrial laser scanners. *Proceedings of the 11th FIG Symposium on Deformation Measurements*, Santorini, Greece.

Gordon, S. and Lichti, D. 2007. Modelling terrestrial laser scanner data for precise structural deformation measurement. *Journal of Surveying Engineering*, 133, pp.72-80.

Grant, D., Bethel, J. and Crawford, M. 2012. Point-to-plane registration of terrestrial laser scans. *ISPRS Journal of Photogrammetry and Remote Sensing*, 72, pp.16-26.

Grant, D., Bethel, J. and Crawford, M. 2013. Comparative study of two automatic registration algorithms. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5/W2), pp.91-95.

Gruen, A. and Akca, D. 2005. Least squares 3D surface and curve matching. *ISPRS Journal of Photogrammetry and Remote Sensing*, 59(3), pp.151-174.

Gumus, K., Erkaya, H. and Soycan, M. 2013. Investigation of repeatability of digital surface models obtained from point clouds in a concrete arch dam for monitoring of deformations. *Boletim Geodesicas de Ciencias*, 19(2), pp.268-286.

Habib, A., Detchev, I. and Bang, K. 2010. Comparative analysis of two approaches for multiple surface registration of irregular point clouds. *International Archives of Photogrammetry and Remote Sensing and Spatial Information Science*, 38(1), pp.61-66.

Han, J. Y. 2010. A noniterative approach for the quick alignment of multistation unregistered LIDAR point clouds. *IEEE Geoscience and Remote Sensing Letters*, 7(4), pp.727–730.

Han, J., Guo, J. and Jiang, Y. 2013. Monitoring tunnel profile by means of multi-epoch dispersed 3-D LIDAR point clouds. *Tunnelling and Underground Space Technology*, 33, pp.186-192.

Hancock, C. M., Roberts, G. W., Bisby, L., Cullen, M. and Arbuckle, J. 2012. Detecting fire damaged concrete using laser scanning. *Proceedings of FIG Working Week*, Rome, Italy, May 6-10.

Lague, D., Brodu, N. and Leroux, J. 2013. Accurate 3D comparison of complex topography with terrestrial laser scanner: application to the Rangitikei canyon (N-Z). *ISPRS Journal of Photogrammetry and Remote Sensing*, 82, pp.10–26.

Lerma García, J. L., Van Genechten, B., Heine, E. and Santana Quintero, M. eds. (2008) *3D Risk Mapping. Theory and Practice on Terrestrial Laser Scanning. Training Material Based on Practical Applications*. Valencia, Universidad Politécnica de Valencia.

Li, Q. D. and Griffiths, J. G. 2000. Iterative closest geometric objects registration. *Computers and Mathematics with Applications*, 40(10–11), pp.1171–1188.

Li, J., Wan, Y. and Gao, X. 2012. A new approach for subway tunnel deformation monitoring: high-resolution terrestrial laser scanning. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 39(B5), pp.223-228.

Lichti, D. D., Gordon, S. J. and Stewart, M. P. 2002a. Ground-based laser scanners: operations, systems and applications. *Geomatica*, 56(1), pp.21-33.

Lichti, D. D., Gordon, S. J., Stewart, M. P., Franke, J. and Tsakiri, M. 2002b. Comparison of digital photogrammetry and laser scanning. *Proceedings of CIPA WG 6 International Workshop on Scanning Cultural Heritage Recording*, Corfu, Greece, September 1-2, pp.39-44.

Lichti, D. D. and Gordon, S. J. 2004. Error propagation in directly georeferenced terrestrial laser scanner point clouds for cultural heritage recording. *Proceedings of FIG Working Week*, Athens, Greece, May 22-27.

Lindenbergh, R. 2013. Trends in detecting changes from repeated laser scanning data: *Proceedings of the Joint International Symposia on Deformation Monitoring*, Nottingham, United Kingdom, September 9-10.

Lindenbergh, R. and Pfeifer, N. 2005. A statistical deformation analysis of two epochs of terrestrial laser data of a lock. *Proceedings of Optical 3D Measurement Techniques VII*, Vienna, Austria, 2, pp.61-70.

Lindenbergh, R. and Pietrzyk, P. 2015. Change detection and deformation analysis using static and mobile laser scanning. *Applied Geomatics*, 7, pp.65-74.

Lindenbergh, R., Uchanski, L., Bucksch, A. and van Gosliga, R. 2009. Structural monitoring of tunnels using terrestrial laser scanning. *Reports on Geodesy*, 2(87), pp.231–239.

Little, M. J, 2006. Slope monitoring strategy at PPRust open pit operations. *Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering*, The South African Institute of Mining and Metallurgy, Symposium Series 44, pp.211-230.

Lovas, T., Barsi, A., Detrekoi, A., Dunai, L., Csak, Z., Polgar, A., Berenyi, A., Kibedy, Z. and Szocs, K. 2008. Terrestrial laser scanning in deformation measurements of structures. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 37(B5) pp.527-532.

Lu, D., Mausel, P., Brondizio, E. and Moran, E. 2004. Change detection techniques. *International Journal of Remote Sensing*, 25(12), pp.2365-2407.

Masuda, T. and Yokoya, N. 1995. A robust method for registration and segmentation of multiple range images. *Computer Vision and Image Understanding*, 61(3), pp.295-307.

Mechelke, K., Sternberg, H. and Keller, F. 2013. A monitoring system with TLS sensor. *Proceedings of the Joint International Symposium on Deformation Monitoring*, Nottingham, United Kingdom, September 9-10.

Mohamed, A. and Wilkinson, B. 2009. Direct georeferencing of stationary LIDAR. *Remote Sensing*, 1, pp.1321-1337.

Monserrat, O. and Crosetto, M. 2008. Deformation measurement using terrestrial laser scanning data and least squares 3D surface matching. *ISPRS Journal of Photogrammetry and Remote Sensing*, 63, pp.142–154.

Okatani, I. S. and Deguchi, K. 2002. A method for fine registration of multiple view range images considering the measurement error properties. *Computer Vision and Image Understanding*, 87(1–3), pp.66–77.

Paffenholz, J, A. and Kutterer, H. 2008. Direct georeferencing of static terrestrial laser scans. *Proceedings of FIG Working week*, Stockholm, Sweden, June 14-19.

Park, H. S., Lee, H. M., Adeli, H. and Lee, I. 2007. A new approach for health monitoring of structures: terrestrial laser scanning. *Computer-Aided Civil and Infrastructure Engineering*, 22(1), pp.19–30.

Pesci, A., Teza, G., Bonali, E., Casula, G. and Boschi, E. 2013. A laser scanning-based method for fast estimation of seismic-induced building deformations. *ISPRS Journal of Photogrammetry and Remote Sensing*, 79, pp.185-198.

Reshetyuk, Y. 2009. *Self-calibration and direct georeferencing in terrestrial laser scanning*. Doctoral Thesis in Infrastructure, Royal Institute of Technology (KTH), Stockholm, Sweden.

Rusinkiewicz, S. and Levoy, M. 2001. Efficient variants of the ICP algorithm. *Proceedings of 3-D Digital Imaging and Modelling* (3DIM), IEEE, Piscataway, NJ, pp.145-152.

Scaioni, M. 2012. On the estimation of rigid-body transformation for TLS registration. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 39(B5), pp.601-606.

Schäfer, T., Weber, T., Kyrinovič, P. and Zámečniková, M. 2004. Deformation measurement using terrestrial laser scanning at the hydropower station of Gabcikovo. *Proceedings of INGEO 2004 and FIG Regional Central and Eastern European Conference on Engineering Surveying*, Bratislava, Slovakia, November 11-13.

Schneider, D. 2006. Terrestrial laser scanning for area based deformation analysis of towers and water dams. *Proceedings of 3rd IAG/12th FIG Symposium*, Baden, Austria, May 22-24.

Schuhmacher, S. and Böhm, J. 2005. Georeferencing of terrestrial laser scanner data for applications in architectural modelling. *Proceedings of the ISPRS Working Group V/4 Workshop 3D-ARCH: Virtual Reconstruction and Visualization of Complex Architectures*, Mestre-Venice, Italy, August 22-24.

Segal, A., Haehnel, D. and Thrun, S. 2009. Generalized-ICP. *Proceedings of Robotics: Science and Systems*, Seattle, USA, June 28-July 1.

Shan, J. and Toth, C. K. eds. 2009. *Topographic Laser Ranging and Scanning: Principles and Processing*. Boca Raton, CRC Press.

Staiger, R. 2003. Terrestrial laser scanning – technology, systems and applications. *Proceedings of 2nd FIG Regional Conference*, Marrakech, Morocco, December 2-5.

Teza, G., Galgaro, A., Zaltron, N. and Genevois, R. 2007. Terrestrial laser scanner to detect landslide displacement fields: a new approach. *International Journal of Remote Sensing*, 28, pp.3425–3446.

Tournas, E. and Tsakiri, M. 2008. Deformation monitoring based on terrestrial laser scanner point cloud registration. *Proceedings of 13th FIG Symposium on Deformation Measurement and Analysis and 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering*, LNEC, Lisbon, May 12-15.

Tsakiri, M., Lichti, D. and Pfeifer, N. 2006. Terrestrial laser scanning for deformation monitoring. *Proceedings of 12th FIG Symposium*. Baden, Austria, May 22-24.

Tsakiri, M., Stathas, D., Bithas, A. and Valanis, A. 2005. Methodology for testing terrestrial laser scanners. *Proceedings of 1st National Conference on Metrology*, Athens, Greece, November 12-12.

van Gosliga, R., Lindenbergh, R. and Pfeifer, N. 2006. Deformation analysis of a bored tunnel by means of terrestrial laser scanning. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36(5) pp. 167-172.

Vezocnik, R., Ambrozic, T., Sterle, O., Bilban, G., Pfeifer, N. and Stopar B. 2009. Use of terrestrial laser scanning technology for long term high precision deformation monitoring. *Sensors*, 9, pp.9873-9895.

Walton, G., Delaloye, D. and Diederichs, M. S. 2014. Development of an elliptical fitting algorithm to improve change detection capabilities with applications for deformation monitoring in circular tunnels and shafts. *Tunnelling and Underground Space Technology*, 43, pp.336–349.

Wang, J. 2013. Block to point fine registration in terrestrial laser scanning. *Remote Sensing*, 5, pp.6921-6937.

Wujanz, D., Krueger, D. and Neitzel, F. 2013. Defo scan++: surface based registration of terrestrial laser scans for deformation monitoring. *Proceedings of the Joint International Symposia on Deformation Monitoring*, Nottingham, United Kingdom, September 9-10.

Yang, B. and Zang, Y. 2014. Automated registration of dense terrestrial laser scanning point clouds using curves. *ISPRS Journal of Photogrammetry and Remote Sensing*, 95, pp.109-121.

Zhang, Z. 1994. Iterative point matching for registration of free-form curves and surfaces. *International Journal of Computer Vision*, 13(2), pp.119–152.

Zhang, D., Huang, T., Li, G. and Jiang, M. 2012. Robust algorithm for registration of building point clouds using planar patches. *Journal of Surveying Engineering*, 138, pp.31-36.

Zogg, H. M. and Ingensand, H. 2008. Terrestrial laser scanning for deformation monitoring - load tests on the Felsenau viaduct (CH). *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 37(B5), pp.555-562.