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PRECISE DETERMINAION OF THE 3D ROOF LAB RAILWAY TRACK WITH GROUND-BASED LASER SCANNING TECHNOLOGY AND ITS RELEVANCE TO HIGH SPEED RAILWAY TRACK MONITORING

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ABSTRACT

In order to determine the relative or absolute railway track and foundation deformation, ground-based laser scanning technology is utilised in this study to attain a precise 3D track reference. Located at the University of Nottingham's Innovation Park, the newly built Nottingham Geospatial Building, where the Nottingham Geospatial Institute is based, has a roof laboratory that has unique testing facilities. This includes a mini railway track of 120m in length and other long-term monitoring monuments. A test was performed to precisely determine the ground-truth location of the railway track using a phase-based laser scanner for the formation of a standard reference. A real three dimensional mesh of the laser scanning data forms the basis for the line extraction. The compactly supported radial basis function (CS-RBF) was employed to determine the track features based on a 3D mesh approach. To verify the achievable accuracy of laser scanning technology, ground truth points measured with geodetic methods are compared with the extracted sample points and the results are presented in this paper.

KEYWORDS: Railway Track. Ground-Based Laser Scanning. Collision Modelling. Deformation of High Speed Railway.

INTRODUCTION

Due to the rapid increase in the mileage of high speed railways in China in the recent years, a challenging task for the railway authorities is how to precisely monitor the health conditions of the foundations and track. Establishment of a standard reference for a section of railway track is the prerequisite for the determination of the relative or absolute track and foundation deformations. Deformations can then be estimated through comparing the established standard reference with the measurements gathered from regular field observations. In this case using a dedicated monitoring platform with high precision dynamic positioning and orientation capacity is an ideal solution for the determination of the micro changes of the railway track and foundations. In order to enhance the usage of a precision dynamic position system in the deformation analysis of tracks and prove the concept, ground based laser scanning technology is utilised by the authors to attain a precise 3D track reference and identify the potential 3D deformations.

Located at the University of Nottingham's Innovation Park the newly built Nottingham Geospatial Building (NGB), where the Nottingham Geospatial Institute (NGI, formed from the former Institute of Engineering Surveying and Space Geodesy (IESSG)) is based, has a unique roof laboratory. The main component of this laboratory includes a pinched obround shaped mini railway track of 120m long and 184.15mm gauge. This laboratory has been constructed for dynamic positioning system research and testing (Figure 1). The track is equipped with a custom built remote controlled electric locomotive that has been designed to carry different grades of inertial units and other state-of-the-art location sensors such as geodetic and bespoke GNSS and Locatalite (a kind of pseudolite) receivers. The locomotive platform has the capability to provide sub-centimetre level real-time positioning accuracy that has been extensively used for developing and validating integrated navigation and positioning solutions. In this study the overall objective is to precisely determine the ground truth location of the railway track using a phase-based laser scanner for the formation of a standard reference. Details about how to set up the field data acquisition procedures to achieve millimetre level positioning accuracy, a 3D mesh approach for track feature extraction, and the use of the collision modelling method to detect abnormal points of the railway tracks (a simulated one in this case), are introduced in the paper. To estimate the achievable accuracy of laser scanning technology, ground truth points measured with other geodetic location methods are compared with the extracted sample points and the results are presented in the paper. It is anticipated that similar procedures could be employed in the monitoring of the real-world high speed railway tracks.

Fig.1 The mini railway track on the roof of the NGB at the University of Nottingham.

MEASUREMENTS OF THE ROOF LAB RAILWAY TRACK

The number and location of the scanning stations and the observation schemes are optimally designed to achieve a maximal coverage and the highest accuracy. This includes considering the layout of the features such points, lines, polygons and cubes, and setting up adequate and precise ground truth points (scanning targets and sample points on the track) for the data extraction.

A real three dimensional (3D) mesh of the laser scanning data is the basis of the feature extraction. In this study a compactly supported radial basis function (CS-RBF) is used to determine the sphere of the point cloud, which could be used to search neighboring points among the point cloud [1]. The advantage of the 3D mesh of the point cloud includes the avoidance of the misconnection of irrelevant points, and its high fidelity to real world features. Based on the obtained 3D mesh, a nominal vector is calculated for each mesh triangle as a geometric indicator of the 3D mesh of the point cloud data. So the level of detail (LOD) in the 3D model of the track could be precisely established. Furthermore, 3D trajectories along the track model could be extracted by tracing the feature points if the gradient changes exceed a given threshold. Finally, the 3D presentation of the fixed track is obtained.

A collision model is used to identify the abnormal laser scan points if a gradient change is manually added at some sections of the track, and this identifies the location of track deformation. In addition, ground truth points are introduced to test the accuracy estimation of the obtained 3D track reference, which helps to demonstrate the feasibility of the track feature extraction method and its achievable accuracy.

The authors of this paper attempt to verify the feasibility of using laser scanning technology to establish a standard 3D model of a fixed track. The ground truth model is important for calibrating the resuts attained from dynamic positioning research and testing. Through comparing the data sets obtained from different observation periods with the reference, the track deformation can be identified. So its significance is evident in deformation monitoring of high speed railways.

METHODOLOGY OF TRACK EXTRACTION FROM LASER SCANNING DATA

Track extraction from laser scanning data is the objective of the work, and the flow chart in Figure 2 explains the methodology used in data processing. The procedure can be divided into three sections: Firstly, an approximating 3D mesh from the laser scan data uses an adaptive compactly supported radial basis function (CS-RBF) algorithm, which approaches the real world features precisely and avoids the misconnection of irrelevant points that is evident in a two-dimensional TIN (Figure 3) **[1]**; secondly, the triangles are searched for the feature points by a multistep vertex normal manipulation **[6]**; and thirdly, the final procedure is to connect the line segments with the excellent Berkeley natural boundary detector to form the complete track **[5]**.

Fig.2 Procedure of the methodology.

Comparing the result with the ground truth points captured with those of a survey total station, the experiment results show that this method is successful in terms of efficiency and feasibility. Actually, a real three-dimensional mesh of the scaning data is the basis of the line extraction, which can be used to search for feature points among the point cloud. The advantage of a three-dimensional mesh of scanning points is that it can avoid the misconnection of irrelevant points, and makes the 3D mesh approach match the real world features very well.

a. TIN model b. CS-RBF model

Fig. 3 Comparison between TIN and CS-RBF models.

Based on the obtained 3D mesh, a vertex normal is calculated for each mesh triangle as a geometric indicator of the 3D mesh of scan data, and a 3D construction is also conducted. By considering the normal vector of the 3D mesh, a gradient of neighboring triangles is calculated to determine the feature points among the point cloud, and some line segments can be obtained by connecting these feature points. As the aim of the work is to attain the whole railway track, an iterative procedure connection algorithm is used to connect line segments and smooth the obtained lines. The mathematic procedure is described in detail as:

Vertex normal approximation

For line extraction that is based on a 3D mesh, a multi-step procedure was employed for line feature detection and connection **[6]**. After the 3D mesh was polygonized, suppose a pair of lists $S=\{V,F\}$ is a representation of triangle meshes. $V=\{v_i:1\le i\le n_V\}$ is a list of faces and each face $f_k=\left(i_1^k,i_2^k,i_3^k\right)$ is a term of non-repeated indices of vertices. Firstly, estimate the per-vertex normal using common algorithms that are based on 1-Ring neighbourhood faces **[3]**.

$$N_{v_i}=\frac{\sum_{f_k\in F^i}|f_k|N_{f_k}}{\left\|\sum_{f_k\in F^i}|f_k|N_{f_k}\right\|},\qquad S=\{V,F\} \tag{1}$$

Where N_{f_k} is a defined unit length normal vector on each face f_k. F^i denotes the set of faces that contain vertex v_i. f_k belongs to F^i.

The normal vector is perpendicular to the surface at a given point. To approximate by a mesh, we need to estimate the unit normal vector $N = \{n_1, \cdots, n_M\}$ at the points of v_i. Scattered points can be equipped with the unit normal that can be directly estimated from the scan range. The normal vector is estimated using a standard covariance-based technique. A vertex normal is then calculated from an adjacent polygon normal. Vertices shared between polygons will have the same vertex normal, and hence the same intensity.

Fig. 4 Angles between vertex and its geodetic neighbourhoods.

Feature point detection

The next issue in the multi-step manipulation is how to decide whether an interested vertex locates on salient feature parts with high curvature or not. The variation of angles between the vertex and its geodetic neighbourhood can be used to make a judgement for this issue. From Figure 4, v is the feature vertex. v_i, v_j are geodetic neighbourhood belong to v, N, N_i, N_j are the vertex normal vectors associated with v, v_i, v_j attained by using the 1-Ring neighbourhood method in advance, and θ_i is the angle between v and v_i.

$$\theta_i = \arccos \frac{N \cdot N_i}{\|N\| \cdot \|N_i\|} \tag{2}$$

There is a set $\Theta = \{\theta_i : i = 1, \cdots, n\}$ for v, and n is the number of the neighbours of v.

The standard deviation of θ_i is:

$$\sigma = \sqrt{\sum_{i=1}^{n} (\theta_i - \bar{\theta})^2}, \qquad \bar{\theta} = \sum_{i=1}^{n} \theta_i / n \tag{3}$$

If $\sigma < \tau$, where τ is a user specified threshold then v is at the low curvature part of the surface, and its normal vector is re-computed with the help of the normal of geodetic neighbourhoods as:

$$N = (N + \sum N_i) / (\|N + \sum N_i\|) \tag{4}$$

One multi-step manipulation for the vertex normal is executed to search the feature points with the help of a user defined parameter τ. If two ridge vertices are detected on the edges of a mesh triangle, they are connected by a straight segment. If all three edges of a mesh triangle contain ridge vertices, the vertices are connected with the centroid of the triangle formed by the vertices.

Edge tracking

Edges are detected by the excellent Berkeley natural boundary detector [2], which was recently successfully applied to object recognition. Next, edges are chained and a smoothed spline curve is fitted to each edge chain, providing estimates of the tangent orientations of the edges.

Due to the well-known brittleness of edge detection, a contour is often broken into several edge-chains. Besides, the ideal contour might have branching, which are not captured by simple edge-chaining. These issues are addressed by linking edge-chains: an edge-chain c1 is linked to an edge-chain c2 if any edge of c2 lies within a search area near an endpoint of c1. The search area is an isosceles trapezium. The minor base rests on the endpoint of c1, and is perpendicular to the curve's tangent orientation, whilst the height points away from c1. This criterion links c1 to edge-chains lying in front of one of its endpoints, thereby indicating that it could continue over c2. The trapezium shape expresses that the uncertainty about the continuation of c1's location grows with the distance from the breakpoint.

GROUND-BASED LASER SCANNING MEASUREMENTS AND DATA PROCESSING

3D roof setup with a FARO focus

For this test a FARO Focus 3D 120 terrestrial laser scanner was used. This is a full panoramic phase based scanner with a maximum range of 120m and a vertical and horizontal field of view of 305° and 360° respectively (Figure 5). The Focus 3D offers high speed measurement with a maximum data collection rate of 976,000 points/sec and also has the ability to be used for mobile scanning. The vertical and horizontal step size of the scanner is 0.009°, producing a maximum scan resolution of 40,960 x 17,352 pixels. Laser diameter at exit is 3.8mm and beam divergence 0.009°.

Fig. 5 FARO Focus 3D for the measurement.

Fig. 6 Figure for the scan locations.

For the scan of the Nottingham Geospatial Building (NGB) rooftop track, a half resolution was chosen giving a scan size of 20,480 x 8,676 pixels and a point separation of 3.068mm/10m. Combining the data collection with colour capture by the internal camera this gave a scan time of just over 9 minutes per scan and a data volume of 650Mb per scan. To enable the NGB track to be captured precisely and at a high resolution, scanning was performed at seven locations across the roof, providing the necessary scan overlap needed for dense point coverage of the surface of the track (Figure 6 for scan locations).

In order to facilitate accurate registration of scan points between separate scans, seven spherical targets were positioned within the scan area. Two different target diameters were used; 2 x ø200mm (FARO Super Spheres) and 5 x ø145mm (FARO Registration Spheres). Throughout the seven scans the targets were repositioned across the roof to ensure their proximity to the scanner and allow for a higher density of scan points on the surface of the sphere and therefore a greater accuracy of target centroid positioning. A minimum of five target spheres remained in position between contiguous scan locations.

The two ø200mm Super Spheres were also used for geo-referencing of the scan points into the British national grid coordinates (OSGB36). In addition to the track there are also seven reference pillars on the NGB roof whose coordinates have been precisely determined through static GNSS measurements over several days. A Trimble S6 1" robotic total station positioned on one of these pillars was used to determine the coordinates of the Super Sphere centroids. Using the total station and tribrach adapter it was also possible to find the coordinates of the Focus 3D origin at the first scan location. The three coordinates from the two Super Spheres and the origin of the Focus 3D were then used to transform the first scan into OSGB36. All subsequent scans could then be transformed into OSGB36 using a combination of Super Spheres and Reference Spheres.

Point Cloud Data Processing

When working with laser scanning data, you have on the one hand the scans with their millions of registered positions, reflectance, and color for each scan point, and on the other hand the overall data processing workspace as well. A data processing workspace contains scans and all the data sets required to process the scan and conduct follow up analysis. Figure 7 is a flow chart for the data processing that includes:

- Measurement schedule, which can point out structural characteristics in a scan.
- Laser scanning setup, which determines the instrument setup in order to obtain the user defined areas of interest in the scans.
- Point registration, which determines the geometric objects identified in a scan and reference to external coordinate systems.
- Point filter and mosaic, which filters the noise points and reduces the quantity of the point cloud before extracting all the different scans points.
- Track extraction, roof railway track extraction based on real 3D mesh of the laser scan data.
- Track application, considering the extracted track features as the known railway location for dynamic positioning testing and deformation analysis.

Fig. 7 Flow chat of the data processing.

Result of the Track Extraction

Scan points are recorded and saved in a coordinate system which is relative to the scanner. The point of origin for this scan coordinate system is the position where the laser meets the mirror. The coordinates of this point are x = 0, y = 0, z = 0. To build the complete model of the roof track we have seven scans taken at different locations. Immediately after data collection the scans will be independent and in their own scan coordinate systems. The origin of these scan coordinate systems will be at different positions on the roof, and therefore it is necessary to determine the spatial relationship between them. Therefore registration of the scan is needed; the step from the individual scan coordinate system into one coordinate system is performed through a transformation. To complete this transformation, reference objects are identified for which scanner based coordinates are known and local or national coordinates can be determined. In this task, more than 3 reference objects in a scan were captured, which is mathematically sufficient to calculate the transformation parameters, i.e. the exact position and orientation of the scan. Then not only the selected reference objects, but also all the scan points had their coordinates determined in the overall coordinate system. After the registration, seven scans are combined and can be analysed from the different views as shown Figure 8.

a. Panorama view from above

b. Panorama view of the whole roof railway track

Fig. 8 View of the point cloud from six scans.

In order to obtain efficient processing, the track point data is extracted from the whole data set. Track extraction is performed based on the data as shown in Figure 9. And the final track line product is obtained as shown in Figure 10.

Fig. 9 Point cloud of the roof railway track.

Fig. 10 3D Track Trajectories Extraction.

In order to estimate the accuracy of the track extraction, some points on the track were observed with a total station as ground truth check points. For comparison, the track features extracted from the scanning data and the ground truth points observed with the total station are both overlaid and displayed in Figure 11 where 16 points along the 120m long track were selected as ground truth points on both sides of the track.

Figure 11 depicts the method used in the comparison of extracted track and ground truth points from which point A, B, and C represent ground truth points while oA means the nearest distance from A to the track. Projecting oA both to the horizontal and vertical plane, we get the distance r, which represents horizontal accuracy while the distance dz shows vertical accuracy. Moreover, if projecting both the track and the ground truth point to a common horizontal plane, the horizontal difference r can be obtained by calculating the radius of a circle centred at A' while tangent with the track's horizontal projection at o'.

Fig. 11 Accuracy determination of the extracted track with ground truth points

By comparing the results, the mean location accuracies of both sides of the track that are extracted based on CS-RBF are 2mm in horizontal and 3mm in vertical. It has been found that the maximum horizontal differences for the extracted track are much smaller compared to the vertical ones. Hence, observation of the detailed figures demonstrates the extracted railway track features based on CS-RBF are more smooth and accurate in the horizontal plane. In conclusion, the railway track extraction in this test proves to be an accurate and feasible approach for obtaining a standard reference track for the future dynamic positioning test purposes, with high relevance to railway track deformation monitoring.

CONCLUSIONS

The experiment has proved that railway track extraction based on laser scanning could be a timely and efficient approach for the determination of highly accurate railway tracks. As shown in the results and the accuracy estimation, the experiment performs successfully with a mean difference less than 2mm in the horizontal plane and 3mm in the vertical plane. Meanwhile, statistics show that this method proves to be better in accuracy and feasibility than other methods for the establishment of a standard geometry of a railway track. Moreover, some factors that caused the differences between the extracted track points and the check points are analysed. The high accuracy (3mm) achieved in the vertical direction with laser scanning method is another factor of the importance to railway track quality. In this case using a dedicated monitoring platform with high precision dynamic positioning and orientation capacity is an ideal solution to the determination of the micro changes of the railway track. In order to enhance the usage of a precision dynamic positioning system in the deformation analysis of a railway track and proof the concept, ground based laser scanning technology could be effectively utilised to attain a precision 3D track reference and identify the potential 3D deformations.

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