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Optical Non-Contact Railway Track Measurement with Static Terrestrial Laser Scanning to Better than 1.5mm RMS

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Keywords: Terrestrial Laser Scanning, Railway Track, Geometry, Deformation Monitoring

SUMMARY

The railway industry requires track to be monitored for a variety of reasons, particularly when any type of physical works take place within the vicinity of the asset (e.g. demolition, construction and redevelopment works). Terrestrial laser scanning (TLS) has considerable potential as a survey method for rail measurement due to its non-contact nature and independence from physical targeting at track level. The consensus from recently published work using static terrestrial laser scanning is that rail measurements to the order of 3mm RMS are routinely possible. Such measures are appropriate for extracting the gauge, cant and twist parameters required by the rail industry, however engineering specifications designed to ensure safe and comfortable running of the trains ideally require measurements of better quality.

This paper utilises standard design rail profiles from the UK industry to optimise the way in which TLS point cloud data are fitted to the rail geometry. The work is based on the use of off the shelf phase-based TLS systems each capable of delivering single point measurements of the order of 5mm to cooperative surfaces. The paper describes a workflow which focuses the fitting process onto discrete planar rail elements derived from the design rail geometry. The planar fitting process is improved through understanding how data from these scanners respond to rail surfaces. Of particular importance is the removal of noisy data from the shiny running surfaces.

Results from a sequence of multi-station TLS surveys of the same set of double tracks taken from platform level highlight the capability to obtain fits to the rail model of better than 1.5mm RMS. Whilst fitting can be carried out on a single side of a rail, the paper highlights the challenge of obtaining an accurate TLS registration necessary to extract both sides of each rail to the same level of accuracy. This configuration is proven over inter-TLS instrument separations of the order of 30m and demonstrates the TLS network coverage necessary to achieve such results even in the presence of an occluding electric third rail.

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1. INTRODUCTION

Within the railway industry, assessing track quality determines the comfort of the ride experience as well as the likely wear and tear of the asset. It's also used to determine the maximum speed at which a train can safely travel over the track before it's at risk of derailment. Track quality is typically measured by a survey system, for example a track trolley (Amberg Group, 2014) or track geometry cars to produce track geometry parameters such as gauge, rail cant and horizontal and vertical geometry (Railway Group standard, 1998).

Monitoring of track is required when any physical works adjacent to the tracks or their supporting mechanisms have the potential to disturb their location or stability. For most monitoring works the impacts are generally related to short range deformations in geometry. Network Rail (the owner and operator of the railway infrastructure in Great Britain) typically specify a measurement of movement to millimetre resolution. It is often the case that the level accuracy is not specifically mentioned and the supplier or contractor is left to determine this themselves. Also, when movement is reported in monitoring systems, statistical analysis of the accuracy is not verified and movements are interpreted at face value.

The instrumentation traditionally used for track monitoring are total stations observing to retro-reflective glass prism targets attached to nearby sleepers or bolts. Despite being an accurate, precise and repeatable system there are some drawbacks of this method. These include the overall cost of the system and time required to setup; the high frequency of occlusions due to passing trains; as well as the reliance on the prism movement physically correlating with the rail movements. Therefore from Network Rail's point of view, ideal attributes of a track monitoring system would include a remote, non-contact and target-less solution accurate to millimetre level that doesn't interfere with normal running trains.

With the developments in TLS technology, such as higher accuracy and speed, it's capabilities as a deformation monitoring tool have been augmented for a wide variety of applications over the past decade (Nuttens et al., 2014; Alba and Scaioni, 2010; Puente et al., 2012).

In order to utilise TLS point cloud data for applications such as monitoring, extraction and segmentation of the relevant features from the point cloud is an integral part of the data processing step (Lari and Habib, 2014). Vosselman et al (2004) state that typical man-made objects such as planes, cylinders and spheres are shapes can be easily extracted from the point cloud based on their geometric parameters. Research into efficient and accurate point cloud extraction procedures has become a wide area of interest and is well reported (Schnabel et al., 2007; Awwad et al., 2010; Lari and Habib, 2014).

An object such as a rail or assembly of objects such as a railway track could be segmented and extracted based on its planar elements by applying accurate local surface fitting. Popular plane fitting methods include Least Squares, Principal Component Analysis and the RANSAC algorithm (Nurunnabi et al., 2012). Each method has its own advantages with respect to robustness, reliability and sensitivity to outliers. The approach used for the work described in this paper utilises the Least Squares method, which is based on the long established principle of minimising the sum of the squared residuals.

Along with the advancement of data acquisition and processing as well as the aforementioned railway industry requirements, investigation into the capabilities of TLS to accurately detect and extract rail track geometry for deformation monitoring has widened in the past two years. Meng et al. (2013) present a laboratory method for extracting track from static TLS data to obtain 3D track reference geometry with the potential to calculate deformations from subsequent scans. An edge detection algorithm was created to produce a trajectory line from a 3D mesh of a laboratory railway track. Results showed a mean difference of 2mm in the horizontal and 3mm in the vertical between the ground truth and the mesh. However it is uncertain as to whether the model conforms to the physical form of the track. Liu et al. (2013) used static TLS to extract track geometry for deformation monitoring of high speed rail to achieve an accuracy of better than 3mm. 1mm cross-sections of track were extracted and then classified using curves and lines based on a given design cross-section. Even though the "noisy" rail head was used for classification, the noise reduction algorithm used and the quality of the scan registration were not described. Both of these could be expected to effect the boundary fitting to the design cross-section. Another classification method, carried out by Soni et al. (2014), also achieved better than 3mm RMS when registering different sections of the track profile (including head, web and foot) to its design rail model. Results demonstrated that data from the rail head was the noisiest part of the section. This was attributed to the phased-based scanner interaction with the complex reflective surface formed on the steel as trains pass over it. The fitting process also included curved parts of the track profile, such as the connection between the web and foot of the rail. Overall it can be seen there is a consensus of achieving accuracies of better than 3mm, however there is a need to improve this level to fulfil the engineer's requirements for track monitoring.

This paper builds upon previous work to optimise the fitting of track point cloud data from a live rail site to a design rail model. The aim is to improve the overall accuracy of track geometry measurements, particularly during monitoring. Section 0 describes the developed methodology from data acquisition to extracting and fitting rail geometry. Section 3 presents and discusses the results obtained from this fitting method, followed by conclusions and proposal of further work in Section 4.

2. METHODOLOGY

2.1 Case Study: London Bridge Station

London Bridge Station is a major transport hub in Central London. As part of the Thameslink Programme, the station is required to undergo a full refurbishment to accommodate the upgrade of the major railway line running through it to allow an increase in the number of passenger carriages as well as the frequency of trains. The station is required to remain operational during the entire project which started in 2012 and is due to finish in 2018. During the refurbishment, the tracks and platforms are required to be monitored throughout the project as they fall within the zone of impact during demolition and construction work. Currently the monitoring system consists of robotic total stations measuring to prisms mounted on the sleeper adjacent to each running rail and on the platform wall along the length of platform and track. For this study an area of track approximately 25m long which was being monitored via total stations was chosen. This section of rail contains 2 running lines with a raised electric third rail running in between these.

A 4-step methodology workflow for the data capture, extraction, cleaning and fitting procedure is shown in Figure 1 and discussed further in Sections 2.2 to 2.5 respectively.

1. Data capture and pre-processing	**2. Rail extraction**	**3. Data cleaning**	**4. Accurate fitting**
1a. Capture scans from platform level (at least 2)	2a. Calculate minimum length of track assumed to be straight	3a. Inspect and remove artefacts and obvious noise from track	4a. Local plane fits of section to determine planarity
1b. Target-based registration	2b. Extract sections of track based on alignment line	3b. Segment planes from cross-section based on design rail geometry	4b. Fit planar sections of point cloud to design rail model to determine quality of fit
1c. Geo-reference scans			

Figure 1: Methodology workflow

2.2 Data Capture

The Leica HDS7000, a phase-based terrestrial laser scanner, was used to scan the test area of railway tracks at London Bridge Station. The manufacturer’s quotes ranging capability of 2 to 3mm MS at the distances employed in this project (Leica Geosystems, 2011). In order to comply with Network Rail’s health and safety regulations of working in proximity to live track, the scanners were setup 1.5m away from the edge of the elevated platform. 2 x 360° scans (Scan A and B) were carried out, one on each side of the platform to ensure both sides of the rail was captured. In order to compare the accuracy of the scans from a longer range, this process was repeated and a second set of scans was setup approximately 25m away (Scan C and D). Figure 2 illustrates the setup, where scan positions are represented by yellow triangles.

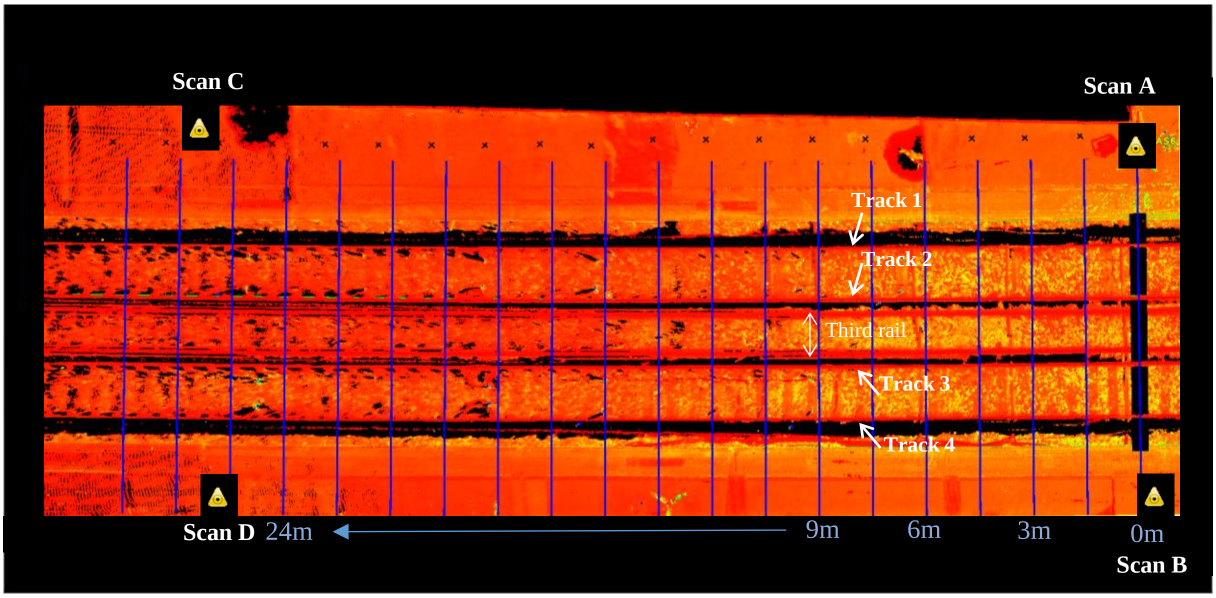

Figure 2: Scanner positions including cross-section locations and track labelling

Black and white tilt and turn checkerboard targets were distributed at various heights across the platforms within the area of interest. Targets were used to achieve the highest possible registration between the scans in Cyclone 8.0.4 (http://hds.leica-geosystems.com/en/Leica-Cyclone_6515.htm). The scans were geo-referenced using a Leica TS15i total station (Leica Geosystems, 2010) and a least squares network adjustment was carried out in MicroSurvey StarNet V7 (http://www.microsurvey.com/products/starnet/). Registration reported a mean absolute error of 1mm. It is important that the registration errors are minimal as this affects the quality of the fits to the design rail model later on. Two scans either side of the tracks was chosen to ensure coverage of all the tracks. Due to the height of the platform and position of third rail, 1 scan alone does not provide enough information for rail fitting. For example, Figure 3 shows the results from Scan A only (top) compared to Scan A and B (bottom) of Track 1-4. Approximate scan positions are represented by yellow triangles. The top of the image shows that despite Track 2 and 4 having suitable coverage from 1 scan, Track 1 is completely occluded by the platform whilst Track 3 has minimal coverage due to the occluding third rail. Therefore in order to carry out sufficient rail geometry extraction, at least 2 scans on either side of the platform is required.

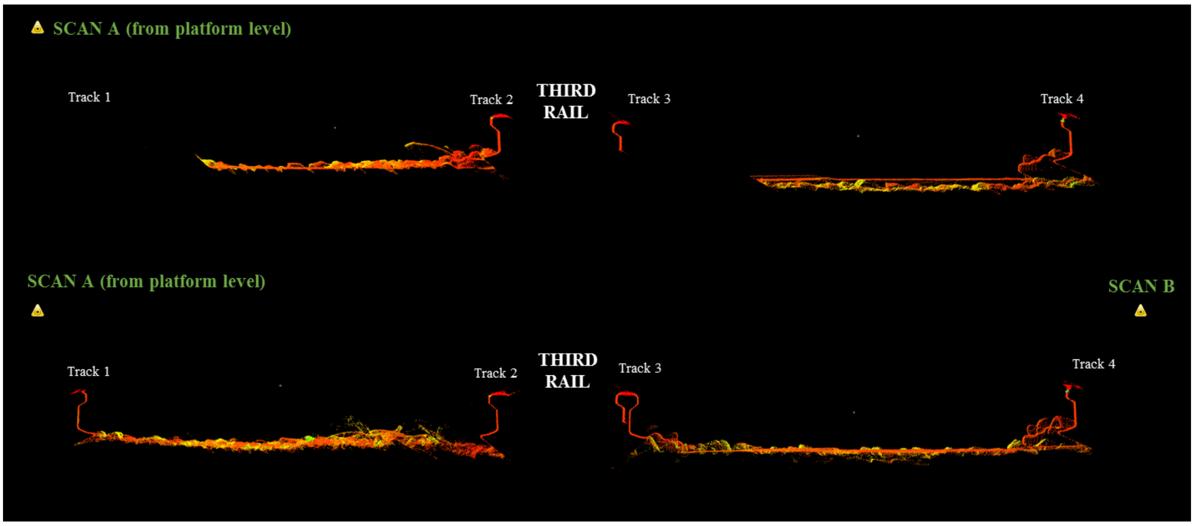

Figure 3: Coverage of track from Scan A only (top) vs. Scan A and B combined (bottom) - NOT TO SCALE

2.3 Rail extraction

Given that scans had been geo-referenced against an established track survey datum (Section 2.2), track detection within the point cloud was not necessary for this study. To ensure accurate fitting to the rail track design model, the track point cloud cross-section must be straight and not curved. The length of the cross-section that can be assumed as straight is determined based on the minimum railway curve radius of the track. In this case study, based on a minimum radius of 90m, 500mm cross-sections can be assumed as straight (with greater than 1mm discrepancy). The sections can then be cut at the appropriate intervals automatically using an alignment line within the Cyclone Sections Manager tool. According to the engineer's monitoring specification, the area of track scanned is required to be monitored at 3m intervals. Therefore 500mm sections were extracted every 3m from both sets of scans (i.e. Scan A&B and Scan C&D). For this paper, the sections extracted from both sets of scans at the 9m interval (shown in Figure 2) are compared. This section was chosen to compare the capabilities of the rail fitting at differing ranges and the effects of angles of incidence from the scanner to the 4 different tracks.

2.4 Data cleaning

The extracted point cloud cross-sections must be cleaned before an accurate fit can be established. A key requirement is to remove obvious artefacts in proximity or attached to the track that will affect the quality of the fitting process. Artefacts include ballast, base plates and track welds. Figure 4 shows an example of an extracted cross-section. The blue circles highlight a feature apparent in the data. On close inspection it can be seen that this feature is a track weld and needs to be cleaned so that it does not adversely affect plane fitting. Even though the plane fitting processes described in Section 1 implements outlier detection, this is not suitable for artefact removal. This is because the artefact to be removed is not comprised of random data but is highly systematic due to the surface that it represents.

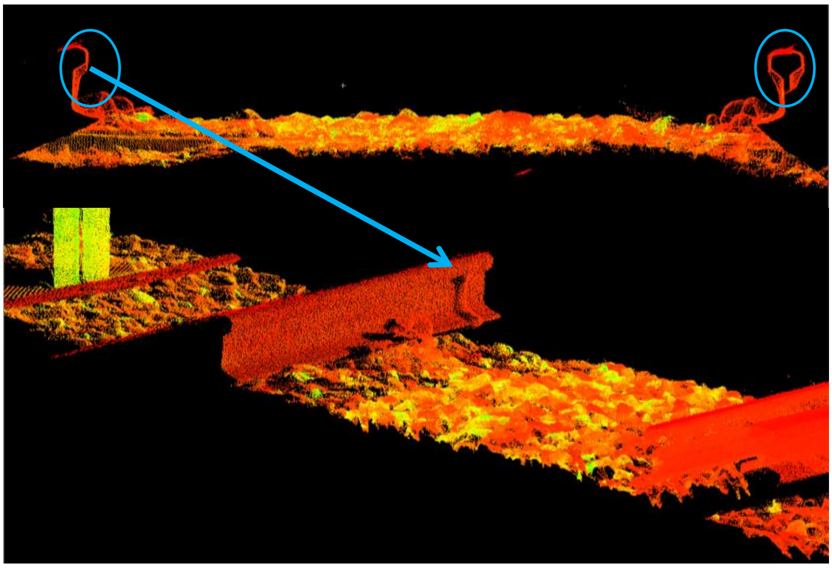

Figure 4: Example of typical artefact associated with the track

This artefact can be automatically removed by applying local plane fitting, using least squares estimation, to the web of the track and analysing the spread of the distribution of the plane fit residuals. In this example the RMS of the fit with the artefact is 2.6mm. Figure 5a shows a histogram of the residuals from the plane fit with the artefact. This graph shows a bimodal distribution with the left peak corresponding to the weld. Isolating this artefact arrives at a better plane fit with an RMS of 0.6mm and the histogram of these residuals in Figure 5b shows a tendency towards a normal distribution.

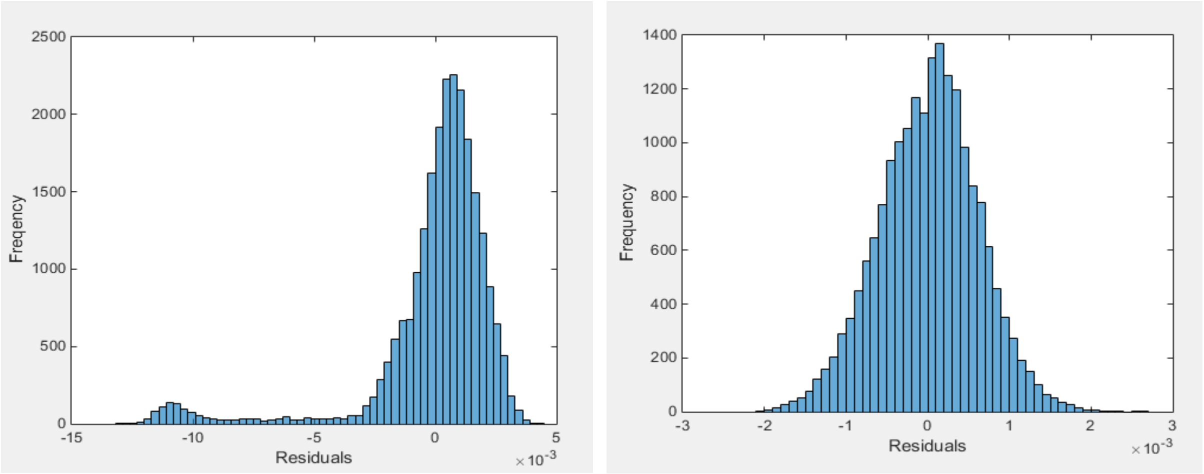

Figure 5a) Histogram of residuals ***without*** *data cleaning of artefacts (left) and 5b)* ***with*** *data cleaning (right) in metres*

This distribution in Figure 5b compares to the residuals of a plane fit to a similar element of reference track scanned in a laboratory, shown in Figure 6.

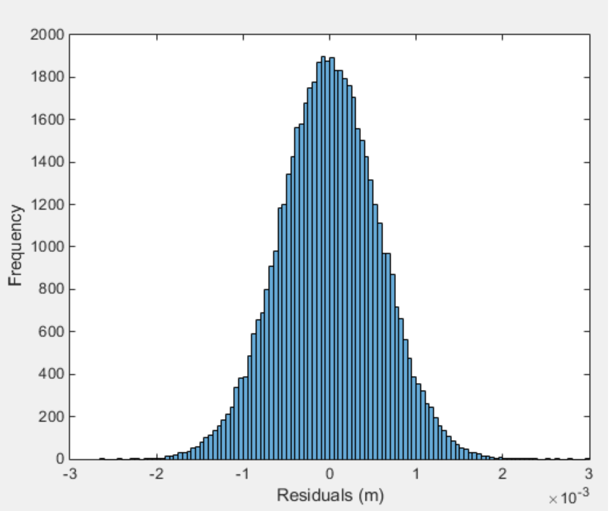

Figure 6 - Histogram of residuals of reference lab track

Despite the shape of the histogram in Figure 6, the residuals from the reference point cloud are not normally distributed which is evidenced by failure of the chi-square test. This is also true for the "cleaned" track data shown in Figure 5b. Therefore the assumption to iteratively remove the secondary peak based on a chi-squared limit test cannot be readily adopted. However it can be seen that there is consistency in the offset between the histograms and upon further inspection a consistent offset of 0.3mm from 0.0mm in both histograms could be seen. Therefore ongoing work is required to form a robust statistical process, but it is clear from the plot of reference residuals that planes can be used for artefact removal.

2.5 Rail fitting

The associated standardised rail model for the track used in this test area was used as the reference model. In order to carry out fitting, the planar areas of the design rail geometry were established by taking a cross-section and fitting planes to each of the segments of track using CloudCompare version 2.5.5.2 (http://cloudcompare.org/). Figure 7 highlights the planar areas of the cross-section in red.

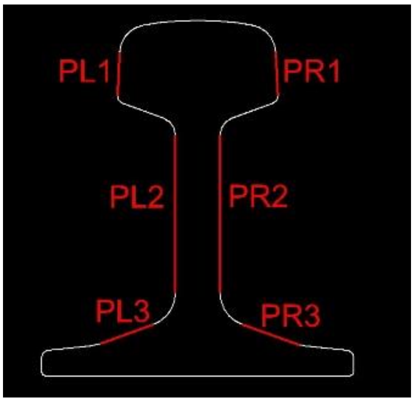

Figure 7: Design rail geometry highlighting planar segments (in red)

Figure 7 was used as a reference model to segment the planar sections of the point cloud. All 6 sections are not visible on each of the 4 tracks, due to the raised third rail or platform occlusions. However the scans do pick up at least 3 of the planes on one side of the track which is a minimum requirement when fitting the point cloud to the design rail model. For example, after cleaning the point cloud, Track 1 (refer to bottom of Figure 3) contains PR1, PR2 and PR3.
Once the point cloud had been segmented into the planar sections, local plane fits were applied to each section. This was to highlight the capabilities of the scanner as well as confirming the planarity. Secondly a series of fine registrations in CloudCompare, using its default ICP algorithm, was carried out to see how accurately the point cloud aligned to the reference model. Results are shown in Section 3.

3. RESULTS AND ANALYSIS

3.1 Track visibility

Table 1 shows the visibility (in green) of the 6 planes for each of the tracks. It can be seen that the 9m interval cross-sections, some of the planes are not visible to the scanner due to occlusions from the raised third rail.

Track Number	= visible	Planar Segment Visibility					
		PL1	PL2	PL3	PR1	PR2	PR3
	Track 1				visible	visible	visible
	Track 2	visible	visible	visible	visible *	visible *	
	Track 3	visible *	visible *		visible	visible	visible
	Track 4	visible	visible	visible			
* = plane not visible at 9m interval due to raised third rail occlusions from Scan C&D							

Table 1: Track visibility of planar features

3.2 Local plane fitting

Local plane fitting, using least squares estimation, was applied to each part of the planar areas of rail track using the software Shapes (Fryer et al., 1992). Results of the RMS of the residuals normal to the plane from Scan A&B and Scan C&D are shown in Table 2.

Local plane fits: RMS of the residuals normal to the plane (mm) from Scan A&B (~9m away)						
	PL1	PL2	PL3	PR1	PR2	PR3
Track 1				0.7	0.7	0.6
Track 2	0.5	0.4	0.6	0.7	0.6	
Track 3	0.9	0.9		0.4	0.4	0.5
Track 4	0.6	0.5	0.5			

Local plane fits: RMS of the residuals normal to the plane (mm) from Scan C&D (~15m away)						
	PL1	PL2	PL3	PR1	PR2	PR3
Track 1				0.7	0.8	0.8
Track 2	0.8	1.0	1.0	n/a	n/a	
Track 3	n/a	n/a		0.4	0.5	0.8
Track 4				1.0	0.8	0.8

Table 2: Local plane fits from Scan A&B (left) and Scan C&D (right)

These results demonstrate the capabilities of the scanner to produce sub-millimetric level of fitting. Despite some occlusions to Tracks 2 and 3, the level of fits are comparable between the setups and different ranges and angles to the same section of track. Overall these data provide a baseline of the expected level of fitting of the track point cloud to the rail model. This expectation can be used as a measure of the quality of the input data and to detect artefacts such as welds and bolts in the vicinity of the rail.

3.3 Point cloud to model fitting

The rail model was considered as a set of discrete planes rather than a single entity (Figure 7). This enabled all registrations to be made using ICP between the raw scan data and the plane definitions. The constituent planes were identified according to the left or right of the rail and are denoted PL1-3 and PR1-3 in both the figure and the tables. Table 3 shows the results from Scan A&B of the cross-section at the 9m interval and Table 4 shows the results from Scan C&D at the same cross-section (shown in Figure 2).

Registration RMS between point cloud to rail model (mm) from Scan A&B									
	Local plane fit registration						Combined plane fit registration (1 scan)	Combined plane fit registration (2 scans)	
	PL1	PL2	PL3	PR1	PR2	PR3	PR1,PR2,PR3 or PL1,PL2,PL3 (i.e. left or ride side of track)	PR1,PR2,PR3, PL1,PL2 (i.e. planes on entire right side and visible left side)	PL1,PL2,PL3,PR1,PR2 (i.e. planes on entire left side of track and visible right side)
Track 1				1.7	1.0	1.4	1.2	n/a	n/a
Track 2	0.6	0.9	0.7				1.2	n/a	1.6
Track 3				0.7	1.3	0.8	1.5	1.6	n/a
Track 4	1.1	1.3	1.1				1.5	n/a	n/a

Table 3: Registration RMS from Scanner A&B

Registration RMS between point cloud to rail model (mm) from Scan C&D									
	Local plane fit registration						Combined plane fit registration (1 scan)	Combined plane fit registration (2 scans)	
	PL1	PL2	PL3	PR1	PR2	PR3	PR1,PR2,PR3 or PL1,PL2,PL3 (i.e. left or ride side of track)	PR1,PR2,PR3, PL1,PL2 (i.e. planes on entire right side and visible left side)	PL1,PL2,PL3,PR1,PR2 (i.e. planes on entire left side of track and visible right side)
Track 1				1.0	1.1	1.2	1.3	n/a	n/a
Track 2	0.8	1.0	1.0				1.2	n/a	n/a
Track 3				0.7	1.1	0.8	1.3	n/a	n/a
Track 4	1.1	1.5	1.2				1.5	n/a	n/a

Table 4: Registration RMS from Scanner C&D

Firstly when comparing the RMS values between both sets of scans for the local and combined plane fits, the results shows the scanner is able to achieve the same quality of fit from 9m and 15m away from the track, despite the number of points on the plane being approximately half at 15m compared to the 9m scanning range with a commensurate change in spot size. The comparability of these show that scanner instrument placement separations could be increased in order to speed up data capture and efficiency. Limiting on-site time and complexity is particularly important given constraints of site access and passing trains.

The RMS of the registration of the local plane fits shown in Table 2 provided a baseline measure against which a target quality for fitting data to the rail model for the TLS system used can be established. The left hand sides of Table 3 and Table 4 highlight that the RMS values of the individual registered fits to the planar segments of the rail model are slightly higher than the target value. This may be due to reduced point cloud coverage on the rail. For example the webs of the track (PL2 and PR2) are always occluded by the side of the head of the rail (PL1 and PR1) when scanning from platform level (Figure 3).

When looking at the registration of the combined plane fits from a single scan location (centre column in tables) that include data from at least 3 planes from one side of the rail, results show a fit of better than 1.5mm to the design rail model. These three planes provide the minimum geometric information necessary for fitting to the rail model. A focus on of the UK rail type and plane fitting has allowed this work to show an improvement by a factor of two compared to previous work where the quality of fit was better than 3mm.

The registration of all visible planes for a particular track collected from scanners located either side of the track and registered together, i.e. Track 2 and 3 with 5 planes, is particularly encouraging. The RMS of the residuals are only 0.1mm higher than the single scan case implying the same quality of fit. However when plotting the histogram of residuals from this case, the histogram has a slight skew to the right (Figure 8). This implies a systematic error in the data, the source of which is most likely to be from errors in the registration between the two scans made on either side of the platform. This highlights the need for accurate registration between the scans, even though in this case an overall RMS of 1mm was reported in the registration in Cyclone.

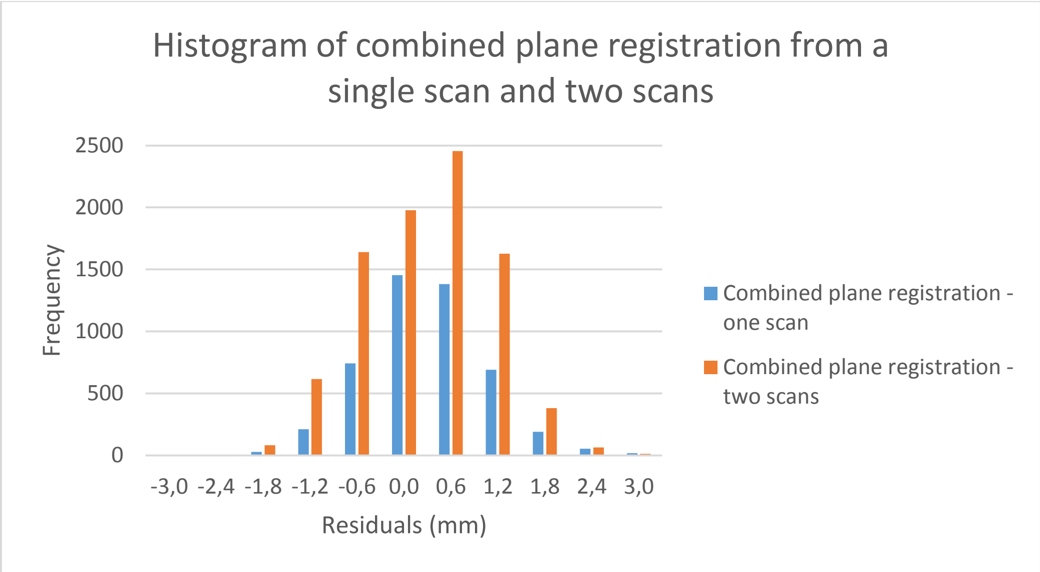

Figure 8: RMS registration residuals of combined plane fitting

4. CONCLUSIONS AND FURTHER WORK

This paper has presented a method to improve the quality of rail fitting a point cloud of track to a UK standard design model by focusing on planar features. Further, by avoiding the highly variable noise produced from the head of the rail in the data captured by the TLS system, the quality of the fit has been improved from a published consensus of 3mm down to 1.5mm and better. This value narrows the gap between engineering requirements for deformation monitoring measurements (i.e. gauge, cant and twist) and what can be achieved from TLS survey. The scans of track from a 9m and 15m scanning range have produced comparable results for both local and combined plane-based registration processes. Given geo-referencing of the order of 1mm RMS achieved in this paper, results indicates separation between instruments of at least 15m should be possible to efficiently scan longer sections of track. The agreement and capability between laboratory and on-site testing demonstrates that laboratory tests of scanning systems can provide a valid acceptancy test for any new technology.

The workflow developed in this paper demonstrates that selection of high quality point cloud of rails is possible given a rail track design model and common co-ordinate datum. Local plane fitting and analysis of histograms of residuals provide a mechanism for removal of unwanted features in close proximity to the rail surfaces and are capable of delivering data of a quality matching that obtainable in the laboratory with a given laser scanner. This process offers significant potential for automation of the optical non-contact rail measurement to the order of 1.5mm with current scanning technology. Further investigation of the systematic bias in the spread of the residuals offers the potential not only to understand the physical interaction between the laser and track surface but also to develop more robust statistical testing procedures to be used for artefact removal. In the future the process is expected to be applicable to both static scanning and scanning from mobile rail mounted systems where careful choice of scanner design may allow further improvement.

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BIOGRAPHICAL NOTES

Anita Soni is currently an Engineering Doctorate student at the Dept. of Civil, Environmental & Geomatic Engineering at University College London (UCL). Her research looks into the potential of non-contact solutions, such as terrestrial laser scanning and photogrammetry, for monitoring railway infrastructure. The study is sponsored by the EPSRC and Network Rail. Before this she worked as a land surveyor at the largest surveying firm in the UK.

Professor Stuart Robson is a Fellow of the RICS and has been working in non-contact optical metrology and engineering measurement since 1990. He leads the 3DIMPact Research Group within the Department of Civil, Environmental and Geomatic Engineering at UCL which seeks to improve the performance and uptake of optical measurement and recording systems for applications ranging from large volume manufacture to very high resolution digital reproduction of museum artefacts.

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