Analysis of railway track transition zones using inertial sensors on an in-service vehicle

Twenty-seven month progress report

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**Background**

This project forms part of a Track21 research programme and aims to measure the condition of track at transition zones where the stiffness of track changes from one section of track to another, using a relatively low-cost system of inertial sensors.

Electronics for an inertial measurement unit (IMU) was developed in the early stages of this project. Two IMUs, a GPS and a logging PC were installed onto one of Southern Railway’s Class 377 EMUs. One of the IMUs is mounted on one of the vehicle’s bogies and one is on board the train. The system also has some other attached measurement devices, which form part of another project at the University of Birmingham which measures third-rail condition.

Software was developed in C# to take data from the IMUs and GPS and store it in a database. The software also allows a number of search and export functions to be performed. For example, all passes of the train though a certain GPS location could be found and exported for further processing. Further and more complex processing has been developed in Mathworks’ Matlab for speed of development, with a view to integrating this into the C# software at a later date.

**Progress to Date**

**Developments in Processing Software**

The software developed to handle the data from the IMUs and GPS now has an additional feature to export directly to Matlab data files, making the transition of data between the software and the Matlab processing much faster.

Further work is in progress to implement a localiser which allows GPS data to be supplemented with the recorded IMU data and an electronic map of the rail network to provide a more accurate location than GPS alone. The localiser is functional but requires some refinement to provide an accurate position. Figure 1 shows a diagram of a junction where two tracks diverge into four tracks. The output of the particle filter in purple and the corresponding GPS location data in green. As the train travels from north to south, it can be seen how the filter corrects itself as it senses a lateral acceleration and a change in yaw measured by the gyro. Some refinement of factors such as coefficient parameters should result in a better estimate of position.
Figure 1: Output from particle filter, shown in purple, with GPS measurements in green

Merging Tacho and GPS Speed Data

A fault with the tacho input to the bogie IMU emerged. The system was unable to accept incoming tacho pulses faster than 1 kHz which roughly translates to $22 \text{ m/s}^1$. For this reason it was necessary to obtain speed information using the GPS at speeds higher than this. It was still beneficial to use the tacho speed data at low speeds as it provides much more consistent speed information. Also GPS speed becomes less accurate at lower speeds due to noise in the calculated GPS location. A method was required to merge the two sources of speed data into a single “composite” speed. To avoid a jump in speed due to discrepancies between the true vehicle speed and the speeds measured by the tacho and GPS, a weighted average of the two sources is used when the GPS speed is between $19.8 \text{ m/s}^1$ and $20.3 \text{ m/s}^1$. Speeds closer to $19.8 \text{ m/s}^1$ are weighted in favour of the tacho, and those closer to $20.3 \text{ m/s}^1$ in favour of the GPS. This provides a smooth transition between the two speed data sources as the train accelerates or decelerates through the speed range where the sensor transition occurs.

A visit to Southern’s depot was arranged to get access to the IMU on board the train and correct the fault with the tacho input. After this, speed could then be ascertained using the tacho alone as a source. The GPS speed may then be used solely for calibration of the tacho speed. The tacho speed varies slightly depending on the circumference of
the wheels which slowly reduce due to wheel wear. Wheel slip may also be a factor, particularly during poor weather, where the tacho may record a different speed to the true vehicle speed. As the axle measured by the tacho for the IMU system is undriven, wheel slip should only ever occur as the train is braking, resulting in a lower recorded speed than the true speed.

A dynamic alignment algorithm was developed to allow variations in speed to be accounted for in the alignment process. This was designed to allow data processed using merged tacho and GPS speed data to be aligned, despite jumps in the measured speed. As the jumps were often severe, the algorithm was never fully able to provide perfect alignment. However, after the tacho interface was corrected and tacho speed alone could be used, the algorithm became unnecessary for comparing relatively short sections of track (~500 m) but is still useful in aligning larger sections of track where the measured distance varies due to the discrepancies between the speed measured by the tacho and the true speed. As these variations are small, the algorithm works well in these situations.

Data with Corrected Tacho Sensor
Figure 2 shows 12 passes of the train over a section of track after the tacho fault had been corrected. Alignment in this figure was done using only a single shift in the X direction with no stretching applied. It can be seen that the alignment is very good even without any further processing.

Manual Alignment GUI
It became necessary to produce some data showing deviation of the vertical geometry of a specific section of track over time. As there was much work still to be done with the dynamic alignment to provide highly accurate alignment, a manual alignment GUI was created in Matlab (see Figure 3), allowing the user to manipulate vertical displacement waveforms to align with one another. This proved to be a very effective way of aligning waveforms, but is quite time consuming to manually align data even from a few passes of the same short section of track (a few hundred metres).
Figure 3: The Manual Alignment GUI developed in Matlab

The GUI allows the user to select passes of the selected location on the right, and align the waveform to an existing pass, shown in light grey on the plotted graph. The selected waveform in blue can be shifted as a whole to coarsely align the data, and then left and right markers (shown in green and red) can be placed on the plot and dragged to stretch or squash the section of waveform between the markers on the X axis.

Once the alignment is complete, the ‘Save Pass’ button is clicked the selected waveform is resampled with the stretches taken into account. The waveform can now be compared accurately to other waveforms aligned in the same way.

Comparing Vertical Displacement Data

Once vertical displacement datasets have been aligned and trimmed to the region of interest, they can be compared to one another. The most basic comparison takes the absolute difference between each data set. Comparing new data sets to an initial one indicates how much each part of the track deviates from the first data set. This is shown in (1).

\[ D_z = |Z_i - Z_0| \]  

(1)

\( D_z \) is the deviation between data sets, \( Z_0 \) is the first vertical displacement data set being observed, and \( Z_i \) is the data set being compared. Figure 4 shows how the results for each data set can be plotted as a horizontal strip with green indicating no change and red indicating a large change. This is done for a number of passes, and each one is stacked allowing changes in the vertical geometry of the track at around 325 m and 343 m to be seen developing over several months.
This type of comparison shows only the absolute change in displacement. However, sometimes the track quality can improve instead of degrade, for example after maintenance or simply through ballast settlement. A graph such as Figure 4 would indicate this as a deviation and could be perceived as a fault. A better method of comparison is to use polarity to indicate an increase or decrease in the magnitude of the deviation, obtained by (2).

\[ E_x = |Z_t| - |Z_0| \]  

Here, \( E_x \) is the deviation in magnitude of vertical displacement. Figure 5 uses the same data sets shown in Figure 4, but shows track degradation (increases in magnitude) in red and improvements (decreases in magnitude) in green. This figure is arguably clearer and one can see that the track at 325 m and 343 m is degrading.
Vehicle Orientation

One factor adversely affecting comparisons is the fact that the orientation of the train, i.e. whether the ‘A’ or ‘B’ cab is leading, changes the measured vertical geometry of the track. Figures 4 and 5 use data from passes all of the same orientation so as not to show any changes caused by orientation. Figure 6 shows 6 forward-facing passes and 6 backward-facing passes of the same section of track. It should be noted that the direction of travel along the track is the same in all passes; only the orientation of the train differs between red and blue data sets.
Initially it was hypothesised that this effect was due to the dynamics of the bogie being affected by the coach above it and the positioning of motored bogies along the train. Figure 7 shows the configuration of bogies on the instrumented 4-car Class 377. It can be seen that in one direction the bogie with the IMU mounted on it would be directly behind a motored bogie, whereas in the other direction it would be directly in front.

Recent work has shown that in fact the positioning of the IMU on the bogie introduces a difference between data recorded in opposing orientations. The Kalman filter used to combine curvature data calculated from the vertical accelerometer and the pitch-rate gyro assumes that the IMU is located in the centre of the bogie. Of course this is impossible, as this is the point on the bogie which supports the coach above it. Figure 8 shows the approximate positioning of the IMU on the bogie which was dictated according to the position of available bolt holes on the bogie.
The measurements made by the pitch-rate gyro are unaffected by the positioning of the IMU because the pitch of the bogie is the same at all points on its top surface. The vertical-sensing (Z) accelerometer measurements however, are affected by the longitudinal position on the bogie (i.e. its proximity to each wheelset). If the IMU were positioned in the centre of the bogie, the Z accelerometer would measure an average of the vertical acceleration of each wheelset. Conversely, if the IMU were positioned directly above one of the wheelsets, the Z accelerometer would measure only the vertical acceleration of that wheelset.

A parameter, $\alpha$, was introduced to the Kalman filter which allows the position on the bogie to be specified. A value of 0.5 would indicate a central position, whereas 0 or 1 would indicate a position directly above one or other of the wheelsets. When the train travels in a reverse orientation (i.e. with the ‘B’ cab leading), the value $1-\alpha$ is used in place of $\alpha$, so that the effective position of the IMU is adjusted appropriately.

Initial results show a much smaller difference between the forward- and backward-facing passes. A small difference remains which could be a result of the dynamics of the coach, or due to the lateral positioning of the IMU. As the IMU is not positioned central to the track, the Z accelerometer will measure a greater proportion of the accelerations from the rail nearest to it, rather than the average of both running rails.

Ideally the system would be able to compensate for the direction of travel so that passes in either orientation could be compared to one another. The effect of the vehicle dynamics, and how this would affect measured geometry using an IMU system is a large work area, and it is felt that this could form another area of research in its own right. The effect measured is very small, and can be ignored for the purposes of this research.

Initial results show a difference in measured geometry at isolated locations as the train travels at different speeds. This constitutes only a small amount of the data in a given set, and could be due to the bogie resonating as particular features are traversed at specific speeds. This could also be due to soft spots in the track support causing the track to sink by a small amount. This would be more apparent at slower speeds as an area of track would spend more time loaded, and potentially sink further. This is an area which could be researched further.

**Future Work Plan**

**The Effect of Speed and Orientation**

Previously it was hypothesised that vehicle speed played a major role in the relatively large variations between some of the passes of specific areas of track. After observing the effect of vehicle orientation, it can be seen that this has a far larger impact than the speed. The Kalman filter has now been adjusted to compensate for vehicle orientation, resulting in a much reduced variation between processed data recorded within a short period of time (~1 month). Some of the remaining variations can be seen to be related to the vehicle operating at a lower than normal speed. The cause of these variations could be an area of further research.

As mentioned previously there is a possibility that the differences in measured vertical geometry are caused by soft track support. There is no way to verify this using the in-service IMU data alone. Ideally a dedicated stiffness measurement device would be used on the track so that reference stiffness data could be acquired. This would be expensive and difficult to arrange for main-line track. The other alternative would be to arrange a one-day trial where a train is temporarily instrumented with an IMU similar to the one on the Southern train, and driven over a private track with previously measured stiffness variations. In a controlled environment such as this, the stiffness variations could even be introduced deliberately, for example by digging out some of the ballast.

**Improved data localization**

Currently the method of extracting data to export to Matlab uses a purely GPS-based method. It is unable to identify the exact track that the train is travelling on if there are multiple tracks in the area. Work to date has largely focused on double-track areas where there is one track running in each direction. In this scenario the track in use can be identified by the direction of travel. A localizer system would allow the position of the train to be tracked on a network map, with the most likely position(s) of the train being kept track of. Only transitions which are physically
possible are allowed (e.g. the train cannot jump from one track to another without a set of points), and retrospective transitions will allow the most likely passage of the train to be amended (e.g. The train could be on one of two tracks, one of which diverges at a set of points. If we later see the train taking the diverging track from the points, we can tell that the train must have previously been travelling on the track which has the points on it).

**Automatic Fault Detection**

One of the main objectives is to automate fault detection. The database containing logged data from the train will be automatically searched to find areas of track which have degraded over time. The advantage of such a system is that track faults can be identified and flagged, after which inspection and repairs could be scheduled.

The current processing requires the user to select a region of interest. Processing and auto-alignment are then applied and comparisons can be made. An autonomous fault detection system would split the area of the rail network that is known to be traversed by the train into sections. Passes of each section of track can then be compared and degradation of the track can be detected automatically. This could be done using a simple thresholding algorithm.

**Publications to Date**


**Other publications not related to this PhD project:**


**Publication Plan**

Abstract accepted for “The Stephenson Conference: Research for Railways”.

Plan to publish in a journal; Automation of fault detection for track data measured using an in-service railway vehicle. This paper will cover the processes used to calculate track geometry, align data sets, and automatically inspect data to detect potential faults and their locations.
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Estimated Submission Date

Thesis submission is currently still expected to be on-target for the end of my third year of study; February 2015. Some areas of work have taken slightly longer than anticipated so it is possible that submission will be delayed by one or two months.