Real-time and post processing of GPS data in the field of visualizing asphalt paving operations

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Abstract. Utilization of global positioning system (GPS) to analyze the movements of machinery during the asphalt paving process is a growing practice. However, the accuracy of GPS measurements is affected by a number of factors that lead to noise in the GPS data. Due to these missing accuracy in the GPS data the asphalt paving professionals have problems interpreting and using the data in their operational context. Therefore, a lot would be gained if the noise in the GPS data could be filtered so asphalt paving operations could be analyzed and improved in greater detail. Filtering, however, is a difficult task. The movements of machinery in asphalt paving are very machine-specific and a high level of detail is required to analyze their operations. For example: Whether a certain pattern in the GPS data is caused by noise or by the machine-specific movement is not easily recognisable. This paper will explore and investigate problems with filtering GPS data and will do so for post-processing as well as for real-time processing. In particular, we analyze two post-processing smoothing techniques for roller GPS data and one real-time processing technique for a paver GPS data. The data were recently gathered on an actual paving project. Smoothing the GPS data will be a crucial step for realistic visualization of movements of machinery at the construction site. Such visuals are vital for operators and decision makers to map, understand, and improve their operational strategies and behaviour.

1 Introduction

For operational control and continuous improvement the asphalt paving process, professionals need to understand the relevant on-site operational parameters, the relationships between these parameters, and the effects of the operational choices on the mechanical properties of the asphalt. To foster such an understanding, the measurement and adequate visualization of the main operational parameters, such as the asphalt temperature, the asphalt cooling, or the movements of asphalt rollers can be of great support (Miller 2010; Miller & Hartmann forthcoming; Krishnamurthy et al 1998) and can give professionals a basic understanding about their actions. Recently Miller (2010) introduced a framework to document the working methods of the asphalt team and show the variability within these methods and the final results. In this framework the movements of machinery are measured by applying global positioning system (GPS) and the asphalt temperature is measured by a combination of a laser-linescanner, thermocouples and infrared cameras. After processing, this results in [a] temperature contourplots, which show the variability of the lay-down temperature of the asphalt behind the paver and [b] compaction contourplots, which show the number of roller passes at specific locations. Our initial experiments show that these plots allow project managers and roller operators to understand globally how homogeneous a certain stretch of asphalt was paved and rolled (Miller 2010).

Production of the contourplots requires GPS precision. The GPS accuracy however is affected by a number of factors generating noise in the GPS data. While the accuracy of GPS measurements can be improved with the set-up of GPS signal relay stations (differential GPS), in practice problems with data accuracy remain - and the set-up of the relay stations is costly and time consuming. The inaccuracy of the GPS-measurements also affects temperature measurements, because these measurements must be 'georeferenced' to a certain location, pinning the temperature data to a certain location at the construction site. Since mix temperature is key in the compaction process and important for operators to make decisions during the process. So, the inaccuracy of the GPS data propagates to inaccuracies in the temperature and compaction contourplots. This makes it more difficult for asphalt paving professionals to understand operational behaviour in detail, for example the number of roller passes in a certain temperature window. Therefore, it is important to filter the noise in the GPS data for the reason of analyzing working methods as well as for representation and interpretation of temperature data.

Movements of different types of rollers and pavers are highly machine-specific. To reconstruct and analyze their behaviour and the applied operational logic, a high level of detail is necessary. For example, rollers work in rolling zones from 30 to 70 meters and these rolling zones are rolled in patterns. So, at a certain point the roller will change direction and drive backwards instead of forwards, passing a so-called turning point. Whether a certain pattern in the GPS data is caused by noise or by a machine-specific movement is for example not easily recognisable on the raw GPS alone. The literature states that these turning points and overlap areas in the rolling patterns can have significant impact on the mechanical as well as the functional properties of the final asphalt pavement (Ter Huerne, 2004; Miller, 2010). Increased accuracy of the GPS data will open the route to better registration of these turning points and the operational strategies at these points.

Analyzing the paving operations, and more specific GPS data and temperature data, is still an intensive post-processing process. Generating visuals as described in Miller (2010) and in Miller and Hartmann (forthcoming) up till now can only be done in retrospect and not in real time. This is useful for lessons and insights to be applied in future projects, but not yet for process control during the project. Therefore, the next step is visualization of GPS and temperature data in real-time to provide the asphalt team with information that would allow them to adjust their operations during the process. So, the add value of higher accuracy of the GPS data is evident. The higher accuracy requires filtering of the raw GPS data. While there is a large body of literature available about GPS data filtering, mainly in the area of navigation, little is still known about filtering GPS data to better describe the operations in asphalt paving. To provide a first stepping stone, this paper presents the first results of our research regarding possibilities of filtering methods for GPS data in post-process procedure and in real-time. The paper is structured as follows: We start with a short introduction of GPS measurement, GPS noise issues and GPS data processing theory. Next, we describe the measurement instruments and methods we used during our data collection exercise at a real construction project. The paper then continues with explaining two data smoothing techniques for post-processing and one technique for real-time data-processing. The paper concludes with the ain findings, their consequences, and an outline of further directions for this line of research.

2 GPS data and curve fitting

The machines in the pacing process are fitted with GPS receivers to register movement and behaviour. Due to inaccuracy in the gathered GPS data, the raw data are ‘predictions’ rather than ‘registrations’ of the actual positions of machinery during paving operations. GPS measurements are (Bouvet et al, 2001): incomplete because they only link to some variables of interest; indirect because they are not directly related to the quantities of interest; intermittent because they are available at irregular spaced time instants; and inexact because they are corrupted by many forms of errors.

The noise in GPS data is mainly caused by the following effects (Xu, 2007): Ionospheric effects (part of the upper atmosphere), tropospheric effects (lowest part of the atmosphere), relativistic effects, earth tide and ocean loading tide effects, clock errors, multipath effects, instrumental biases.

To make sense of GPS satellite signals it is important to transform the incoming GPS signal to a human or computer interpretable format. The literature (see for example Xu, 2007) refers to this as the prediction problem: How can one use a set of observed variables – the GPS signals - to predict unobserved variables – the machine movement. One important first step to solve the prediction problem is to filter stochastic noise in the GPS stream that stems from measurement inaccuracies of the GPS system. Within this prediction problem it is important to distinguish post-processing, where the whole dataset is available or real-time processing, where only a part of the dataset is available. Post-processing allows for interpolation, while real time processing requires extrapolation. Therefore, we separated post-processing filtering methods and real-time processing methods in the next two sections.

Post GPS data processing

One way to filter GPS data in post-processing mode is to use different curve fitting techniques, such as moving average smoothing, digital smoothing, polynomial filter and local regression smoothing. Using span parameters to construct curve with respect to nearby points, makes it possible to involve a certain number of previous and subsequent points for best fitting. Also big players in the market of GPS devices use these fitting techniques (for example uTrack from Garmin). The smoothened GPS path might then be used for further visualization and referred as a less noisy machinery movement path. Pavers only move along the road in one direction without major turns (ideally) and maintain a constant and preferred speed. Speed deviations are more likely than directional deviations. Therefore its' movements can be easily described and simple smoothing techniques might be enough to filter out outliers and keep machinery path consistent in case of GPS signal loss. Compared to the paver data, roller movements is much more problematic – even in post processing. The roller moves with higher speed, has more freedom in space, time, direction and even configuration (a tandem roller has two articulation points). Simple smoothing techniques in this case might lead to loosing valuable data, p.e. the point where the curving or reverse movement start and end. Therefore, we should control the difference between the original coordinates and the smoothed coordinates, so we do not loose valuable data.

Real-time GPS data processing

For real-time GPS data processing more advanced techniques are necessary, since the subsequent datapoint is actually unavailable. Kalman filtering methods are one of the options available to straighten the GPS data in real-time. Kalman filters are commonly applied for mapping of moving objects based on collected position data or for real-time machine guidance applications. Significant improvement of position estimation can be achieved by a combination of differential-GPS and Inertial Measurement Units (IMU) (Inoue et al, 2009) or with WAAS-enabled GPS (system with ground reference stations) and IMU (Linsong et al, 2002). A review of the application of a combination of extended Kalman filters in combination with speed sensors, steering angle encoder and a fiber optic gyro can be found in Rezaei and Sengupta (2007).

Also some applications in the paving domain, for paver and roller position mapping, exist. For example a system based on 3-GPS arrangement, created of three antennae forming an equilateral triangle (Stathas et al, 2001). And estimation of localization of compactors can be based on non-linear system and Extended Kalman filters (Bouvet et al, 2001) aimed to obtain satisfying performances in dead reckoning navigation with low-cost internal sensors.

So, intensive research in the area of a Kalman filtering and its application to construction machinery movements is already carried out and shows a clear demand of improving position-related data on site, where highly precise information is required. In the following sections of this paper we will illustrate how the two different types of GPS data processing can be used to increase detailed information of GPS data during asphalt paving using data we measured on a recent asphalt paving project. First, the next section will describe the experimental set-up at the construction site in more detail.

3 Experimental GPS Measurement Setup

In the past three years we collected GPS data on nine projects in the Netherlands, and on each project for three to four machines – asphalt pavers and rollers. For this paper, we selected the data of two of these nine projects and focussed on the data of one 3-drum roller of one project and one paver of another project.

The GPS measurements were carried out with an on-site installed differential-GPS, since DGPS provides higher accuracy. Following, we transferred the (raw) GPS coordinates from their initial spherical coordinate system into a Cartesian coordinate system and imported the data into Matlab. For post-processing we used Matlab's curve fitting tool to apply the above mentioned fitting techniques. For (simulated) real-time processing we used the Kalman filter implementation in Matlab. The next two sections discuss the outcomes of these two experiments (post-processing and real-time processing) in more detail.

4 Post-processing smoothing techniques to align GPS data-interpretation

Movement of a roller during the compaction process encompasses a number of direction changes. The plot on figure 3 represents the whole raw GPS dataset of the movements of the chosen roller. This overall view provides an impression of the project and about the amount of passes and direction changes during a project. This figure already clearly shows that at some sections of the road more roller passes are carried out than at other sections.

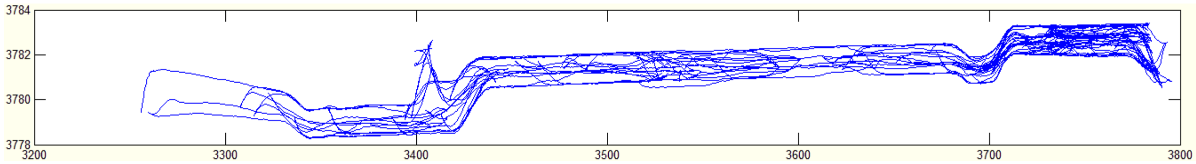
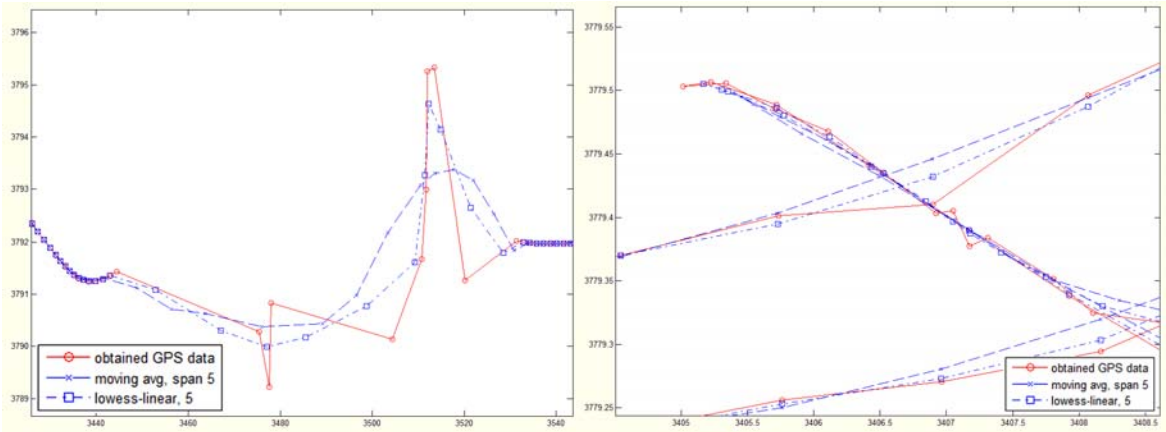


Figure 3: Overall view of compactions passes

It is possible to zoom into specific parts of the curve to examine the data more in detail. Figure 4 displays two enlarged sections of the collected GPS path. Figure 4a shows an example where some points in the GPS data are missing, possibly because the connection was lost shortly. Figure 4b shows an example of a turning-point: The roller slowed down, stopped and started moving into the opposite direction. Looking at these two segments in detail reveals an important problem that needs to be solved to determine the exact location of turning points. It is difficult to discriminate outliers in the data caused by missing points from the turning-points. How can smoothing techniques help in this case?



a b

Figure 4: Compaction by a roller:
a) example of GPS data loss (left); b) 180 degrees turning point (right)

We honed in on 2 smoothing techniques, moving average and lowest linear fit, with appropriate span parameters and analyze the difference between the original and adjusted data points. We carried out the smoothing with a moving average of 5 points and a lowest linear fit of 5 points (figure 5). Independent of the chosen processing technique, we: [a] rotated the machine path for visualization purposes, [b] smoothened the path with the desired technique separately for orthogonal and longitudinal rotated path axes in 1D and [c] analyzed the obtained differences between the original and the adjusted track points. The distinction between orthogonal and longitudinal directions is important because the precision in orthogonal direction is more important than the direction along the road to understand the details of a specific asphalt rolling operation. Therefore, we separated the movement analysis into 2 parts, where each direction is taken as a 1D smoothing task. Using this procedure and the known turning point pattern (slow down, stop and movement in opposite direction), it is possible with these smoothing algorithms to analyze and identify the turning points.

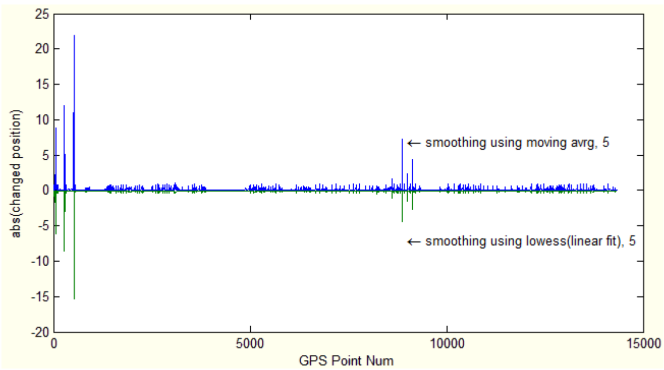


Figure 5: GPS data adjustment using different smoothing techniques

Figure 6a zoomed in on the adjusted GPS data points 8850-9250 which are adjusted by the moving average and the lowest linear fit algorithms. The figure shows that the moving average smoothing algorithm adjusted much larger corrections than the linear fit method. Smoothing using moving average and lowest linear fit may give different outcome at direction changes points. Same applies for relatively quick maneuvers in comparison to overall continuous movement of machinery. Arrows at figure 5 point to large changes of the movement path, depicted at figure 6. The relatively strong path correction near point 8870 (figure 6a) was caused by combination of movement characteristics, shown in figure 6b: speed was higher than average, 180-degrees turn, direction change and GPS data loss for a few seconds. So, by manually or automatically analyzing figure 6b it is possible to identify 180 degrees turning points and apply adjustment using differences between original and smoothed coordinates. To find the turning points it is required to look for patterns: Direction change implies the machine slowing down and distance between GPS points will decrease.

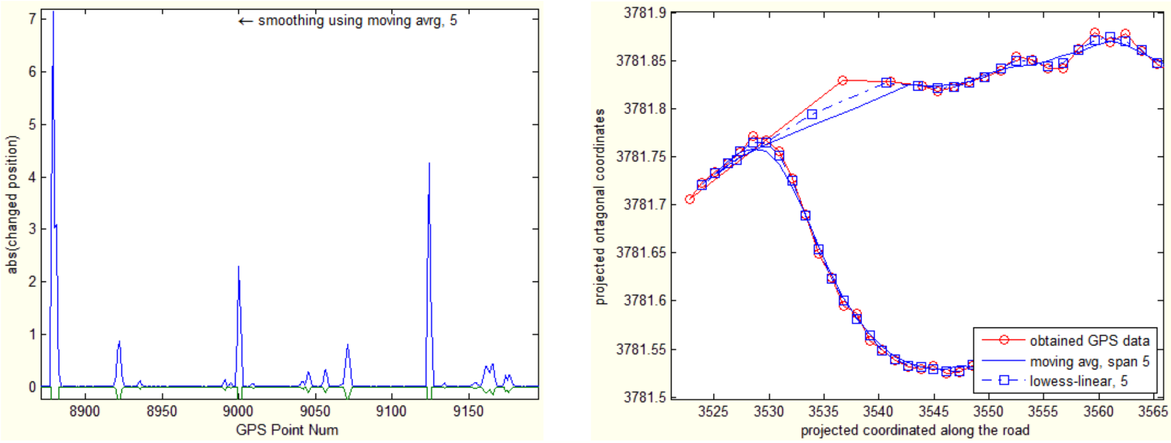


Figure 6: GPS data smoothing:
a) original and adjusted points significantly differ (left);
b) example of using different techniques for 180 degrees turning point (right).

5 Real-time smoothing technique to real-time support operators of the asphalt team

Because movements of the paver can be described more simple – paver behavior is less complex, more constant and consistent – we made our first step towards real-time data-processing with GPS data of a paver. The actual movement of the paver can be validated easily, because the paver generally follows a straight line. We did validate the data for the real movements by calibrating with certain known positions. However, this example still has practical relevance for rollers as noise in the coordinated hinders the exact relation between the measured data to a particular spot on a newly constructed asphalt layer. Therefore additional processing is required. We set up an experiment on a construction site, where the asphalt team had the task to pave a 440 meter long straight road, so we could validate the GPS-data.

To analyze collected coordinates and improve location estimation we used the Kalman filter implementation in Matlab. The current implementation of this filter is actually still a least square method, but we intend to add other sensors in the analysis (possibly with stochastic models) and therefore we used the Kalman filter. As mentioned before, Kalman filters are well-known and often used to work with noisy signals and, in particular, with GPS coordinates. The plot of the data is presented in figure 7 and shows the (raw) original positions with the cross and the coordinates after applying the filter with the dotted line. From this plot one can see that the filter generates a more continuous line of the paver movement. More detailed analysis based on the Matlab curve fitting toolbox output is represented in table 1. Although original and filtered paths have a good fit to the linear movement, the root mean square error and sum of the squared errors have certain differences (values closer to 0 indicate that the model has a smaller random error component).

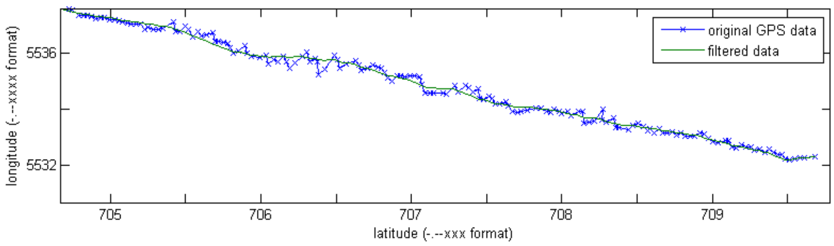


Figure 7: Coordinates of paver received from GPS-receiver and filtered path

Table 1: Validation of the filter

Original coordinates	Coordinates after applying filter
Linear model: f(x) = a•x + b *Coefficients (with 95% confidence bounds):* a = -0.2701 (-0.2703, -0.2699) b = 19 (18.99, 19.01) *Goodness of fit:* SSE: 4.7e-010 R-square: 0.9998 Adjusted R-square: 0.9998 RMSE: 5.422e-007	Linear model: f(x) = a•x + b *Coefficients (with 95% confidence bounds):* a = -0.2701 (-0.2703, -0.2699) b = 19.01 (19, 19.01) *Goodness of fit:* SSE: 3.893e-010 R-square: 0.9998 Adjusted R-square: 0.9998 RMSE: 4.934e-007

The described application of a Kalman filter gives not only better results for a position, but has also more precise orientation (angle and distance from previous point), which in our framework of measurement is valuable for georeferencing the temperature data. The improved paver position once combined with linescanner temperature data produces georeferenced contourplots with higher accuracy and detail, and is considered to be more useful for operators than the time-based temperature contourplots the linescanner generates.

6 Possibilities for future research

One direction for future work is the development of algorithms that can discriminate between outliers and GPS noise from roller turning-points automatically. We expect that the physical characteristics of roller movement, i.e. the maximum speed and acceleration or rotation angle can help us to look for patterns within the data.

Another direction for future work is to explore how accurate the initial GPS measures need to be to allow for sound analysis and representation of roller behavior at turning-points. The GPS data used in the experiment are relatively accurate because of the use of a reference base station (DGPS). The required measurement precision can be reduced through adequate post-processing methods. If this is possible a reduction of the required measurement accuracy will also cut back the overall costs for GPS measurement devices and their setup.

Finally, the presented work shows a trajectory towards real-time data processing and filtering for a paver. However, further research should deal with real-time data processing of rollers that would allow the provision of compaction contour plots and other visualizations during ongoing paving operations.

7 Conclusion

This paper describes two possible post-processing methods to smooth raw GPS-data from rollers in real construction projects and a real-time processing method to smooth GPS-data from a paver in a real construction project. Implementing the smoothing techniques, with some assumed movement limitations, allow us to apply techniques that are typical for sophisticated filtering in a clear and self-descriptive way. The smoothing techniques we applied improved the accuracy of the GPS path data and, hence, will subsequently increase the accuracy of the compaction contour plots.

The paper shows that smoothing of GPS data of roller movements is complex, due to speed and direction changes in the rolling process. Simple smoothing leads to the loss of valuable data, especially at curving and at the turning points. To analyze GPS-measurements of rollers accurately and in more detail it is, therefore, necessary to detect and isolate noise in the GPS data that is caused by measurement inaccuracies and to discriminate these from movement patterns of curving and turning of rollers. This paper reports about first results that can help to operationalize this distinction for the development of automated smoothing algorithms.

For us the presented initial study and results are a stepping stone for future work towards more accurate, more detailed and (more) real-time processing and visualization of the paving operations. We plan that we can, in this way, support the asphalt paving industry to move towards a better understanding of their paving practice.

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