A COST-EFFECTIVE POSITIONING SOLUTION FOR ASPHALT ROLLERS BASED ON LOW-COST DGPS RECEIVERS

by

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ABSTRACT: As of today, the DGPS-based Computer Integrated Road Construction systems for compaction support require high investments (about 50% of total machine cost), mostly due to the high cost of the positioning equipment. Worksite tests show that the majority of the compaction errors are serious omissions of the compaction plan. The article discusses the accuracy requirements and implementation structure of a cost-effective system based on the low-cost DGPS receivers, aimed at detection and correction of the major compaction errors. First results of the experimental validation confirm the feasibility of the approach. The full-scale implementation is currently under development and scheduled for worksite tests. The availability of cost-effective and robust positioning solutions should improve the acceptance of the DGPS-based compaction support systems.

KEYWORDS: compactor pass map; computer integrated road construction; low cost DGPS; positioning; unscented Kalman filter

1. INTRODUCTION

The purpose of the Computer Integrated Road Construction (CIRC) is to increase the quality of the road works by tracking the construction processes in the real time [1]. As the basic concept is based on the comparison of the actual position of the machine's tool with the desired value, e.g. with a digital terrain model (DTM), the positioning sub-system is a crucial element of every CIRC system and greatly influences its performance.

As of today, the CIRC systems use two basic positioning techniques: the Robotic Total Station for high precision measurements (mm range) and Differential GPS (DGPS) receivers for lower accuracy (cm-dm range). The DGPS-based compaction support systems introduced recently, both in research and commercial domain (e.g. [2][3][7]), share the disadvantage of a relatively high price and have not yet found market acceptance. The cost-effectiveness is an especially important factor for the compaction support applications, as the asphalt rollers are considered not cost-intensive machines. Still, the correct compaction is critical for the quality of the asphalt pavement.

For this reason, the cheap positioning solution based on low-cost DGPS receivers has been studied, and is now implemented in the scope of the OSYRIS project [9]. The intermediate results are presented in this paper.

2. MOTIVATION

CIRC products for the broad market must take the total system cost into account. Compared to the total investment costs of an asphalt roller, additional CIRC equipment is still quite expensive (approximately half of total costs), where most of the price is due to the positioning equipment. Therefore it is justified to consider cheaper positioning solutions.

Required positioning accuracy is the critical factor determining the cost. For surfacing machines, such as asphalt rollers, a 2 dimensional positioning, at a working speed between 5 and 10 km/h is required. For this purpose, Peyret [1]

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recommends decimetre accuracy. Also Do et al. [6] suggest an accuracy better than 15 cm, in order to monitor the overlap between consecutive passes.

Existing DGPS systems can be classified according to the used technology, resulting accuracy and price level as follows:[2]

- Centimetre accuracy Phase DGPS with fixed ambiguities – price range 15-25 k€.
- Decimetre accuracy Phase DGPS with floating ambiguities – price range 3-8 k€
- Meter accuracy Code DGPS – price range 0.1-0.2 k€

As of today, the surveying centimetre accuracy receivers are mostly used for compaction support tasks. Due to the limited market, their price has remained high in recent years. The costly GPS differential phase processing has additional disadvantages: low robustness and long initialisation times. This has to be opposed to the widely applied meter-accuracy DGPS, where the market is well-established, applications are numerous and the price reduction has been achieved using specialised integrated circuits. Moreover, the code measurement is much more robust and is available almost instantly, partly due to the relatively simple processing. This is very important in the context of the road construction site, where the satellite visibility may be limited due to pre-existing bridges, urban canyons etc.

The question arises to what extent the code-differential GPS, possibly aided by inertial positioning and Kalman filtering, may be applied in compaction support context. The experimental tests conducted in 1967 in [7] suggest that extremities of the pavement, the join and edge, tend to receive substantially less compaction. In more recent tests [8], the number of passes at many sections vary between 10 and 50, and the compaction plan has clearly not been kept (see Fig. 1.). Apparently this tendency has not changed during last 35 years.

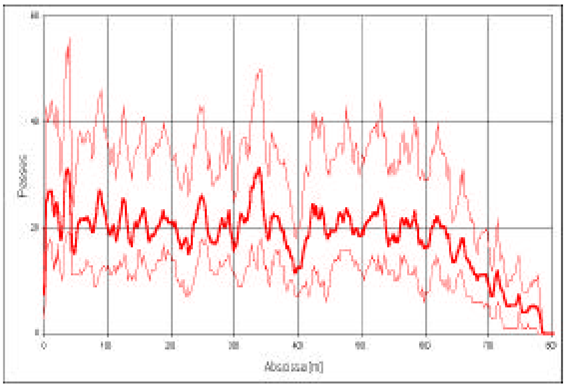

Fig. 1: Minimum, mean and maximum number of drum passes at given curvilinear abscissa measured experimentally on a motorway section.

Clearly, a sub-metre accuracy system would be sufficient to detect and help to correct such major compaction errors. The minimum requirement of the positioning accuracy is posed by the lane definition (typical width 1.8 m). Such level of accuracy can possibly be reached with the Code DGPS. However, it is necessary to investigate the configuration of the sensors and evaluate the resulting accuracy in terms of the man-machine interface (MMI) result.

3. SYSTEM DESCRIPTION

3.1. *Configuration*

The preliminary study has shown that the application of multiple DGPS receivers on one machine offers several advantages:

- Increased precision can be reached by averaging, as the positioning noise of the receivers is only weakly correlated. The achieved improvement of RMS error was close to $2^{-1/2}$. This suggests that the majority of the error is due to the multipath effects, dependent mostly on the antenna placement.
- The heading of the machine can be determined, also in static conditions.
- As the distance between the antennas remain approximately constant, the reliability of the measurement can be monitored.

For practical reasons the number of the receivers has been limited to two, over the front and rear drum. The additional inertial sensors have been introduced in order to provide independent measurements of the machine speeds: linear and angular. The chosen inertial sensors

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[2] As the reference station can be shared, its cost is not taken into account here

are relatively inexpensive and should be integrated in the machine in order to improve the robustness of the system.

Fig. 2. shows the basic structure of the system.

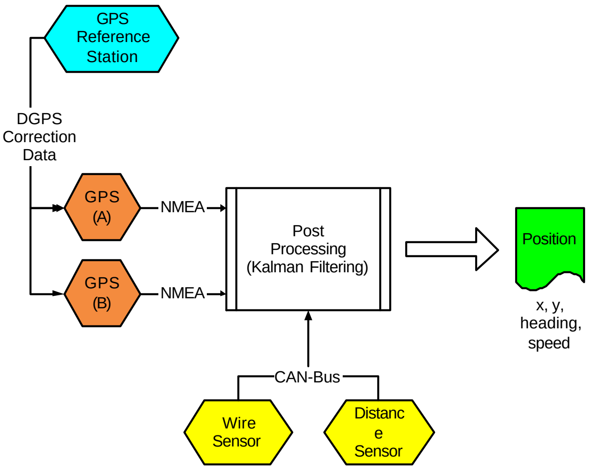

Figure 2: Basic System Structure

The used positioning equipment consist of:

- Two low-cost GPS OEM modules (CEP in DGPS mode < 1 m)[3]
- Two active GPS antennas at the machine extremities
- Wheel odometer
- Optionally: Wire sensor for the articulation angle measurement

The articulation angle measurement can possibly be omitted, as the typical compaction pattern consists of a combination of straight lines, in order to avoid destroying the fresh asphalt surface. The turns are made on already compacted material, with the vibration switched off, and do not have to be counted as passes. However, the articulation angle measurement may be of advantage for curved compaction plans.

The GPS measurements are carried out with 1Hz DGPS mode (with RTCM 2.1 correction messages received from a high quality base station), the inertial sensors work with a measurement cycle of 2..5 Hz.

3.2. *Mathematical Modelling*

Considering a compactor with an articulation joint, moving in the two dimensional space, the location of the vehicle can represented by the state vector

$$X = [x, y, f, v, w]^T \tag{1}$$

where x and y describe the position of the articulation joint, f describes the heading (yaw), v and w denote respectively the translational and rotational speed (see Fig. 3.). Both drums can be modelled by a stick of a length w (equal to the drum width) attached at to the joint. This simplified model can still accurately represent the longitudinal overlaps.

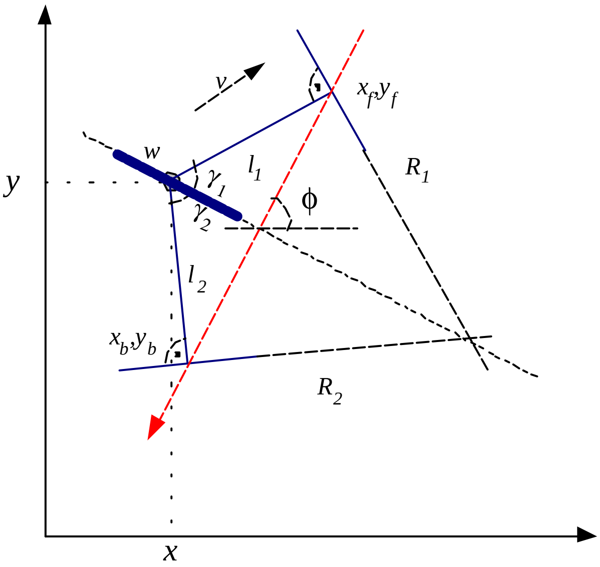

Figure 3: Model geometry

Assuming constant speeds and no lateral slip, and taking into account the articulation angle, the kinematic model is represented by the nonlinear model

$$\dot{X} = F(X) = \begin{cases} \dot{x} = v\cos f \\ \dot{y} = v\sin f \\ \dot{f} = w \\ \dot{w} = v(g - p) \text{ or } 0 \\ \dot{v} = 0 \end{cases} \tag{2}$$

The measurement vector Z includes the position measurement from the front and the rear GPS, placed l_1 and l_2 from the articulation joint, above the front and the rear drum of the roller.

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[3] Manufacturer specifications. CEP, The Circular Error Probability indicates a circle, which encloses 50% of the measured positions.

Moreover the angle and speed measurement are used.

$$Z = \left[x_f, y_f, y_b, y_b, f, v, g \right]^T \tag{3}$$

The discrete system equations can be then written as

$$\begin{aligned} X_k &= F\left(X_{k-1}\right) + V_k \\ Z_k &= H\left(X_k\right) + W_k \end{aligned} \tag{4}$$

where and F and H are system and measurement functions and V, W are additive system and measurement noises.

Based on the estimated speed, a Boolean estimate of the static/kinematic mode can be produced. The passes of the machine are counted only in the kinematic mode.

3.3. The Unscented Kalman Filter

The observations are processed with an Unscented Kalman Filter (UKF). The UKF for nonlinear estimation [4] is based on the Unscented Transformation, presented by Julier and Uhlmann [5].
Consider a recursive estimation

$$\hat{X}_k = X_{k,pred} + K_k \cdot \left(Z_k - Z_{k,pred}\right) \tag{5}$$

for the optimal minimum mean-squared error estimate for X_k, assuming that the prior estimate $\hat{X}_k$ and the state observation Z_k are Gaussian Random Variables.
The UKF extends (5), redefining the state random variable as the concatenation of the original state and noise variables [3]. An unscented transformation sigma point selection scheme is applied to the new augmented state random variable to calculate the corresponding sigma matrix [5]. The UKF algorithm can be found in [4].

Compared to the traditionally applied Extended Kalman Filter (EKF), the UKF offers better performance and adapts better to non-gaussian noise present in this non-linear system. Moreover, as the explicit linearisation is not required, it is easy to test alternative models and filtering structure. The disadvantage is increased computation cost in terms of CPU time and memory.

The full Kalman step is calculated in a 1 Hz cycle, with each new GPS measurement. Assuming a working speed of 2 m/s this results in a real-time uncertainty of 2 m on the MMI, additionally influenced by the GPS latency (< 0.5 s corresponding to 1 m). For these reasons a filter with a 2-5 Hz prediction step and a 1 Hz correction step has been considered.

4. EXPERIMENTAL VALIDATION

To conclude on the accuracy of the presented positioning solution, several static and dynamic tests were performed and evaluated.

As no asphalt roller was available for the first test period, a wheel loader with similar kinematic characteristics was chosen (Fig. 4.). The two GPS antennas are mounted at the front shovel and on a framework at the back, where also the wheel-distance sensor is fixed.

To reduce the multi-path errors, a metallic disc, diameter ~40 cm, is mounted under both antennas. The last tests were performed, using an additional framework at the back, to reach an antenna height of 2.50 m. Also the shovel at the front was lifted, to reach the same antenna height as at the front.

Figure 4: The machine and equipment used in the preliminary tests.

The raw data from the GPS and the inertial measurements are processed, using an UKF filter, with the kinematic model, presented above.

The test results (Fig. 5.) showed that in the static conditions one can observe a drift of the measured position. To account for this effect UKF switches to a static model, represented by:

$$\dot{X}_{static} = F\left(X\right) = 0 \tag{6}$$

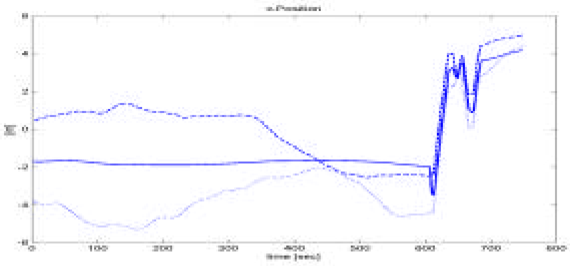

Figure 5: X-coordinate of the position: raw front measurement, raw rear measurement, processed by the Kalman filter

In order to establish the reference for the obtained accuracy, the recorded raw GPS observables (code pseudoranges and integrated carrier phases) have been processed using commercial GPS post-processing software. Its performance can be judged similar to the best GPS receivers available. In this way centimetre-accurate trajectories of both antennas have been measured.

The obtained trajectories together with the heading information have been converted into ribbons [10] and presented as pass maps in the Fig. 6. Except of the overlaps, both maps are qualitatively very similar and give the operator the required overview of the performed compaction work. The major omissions and the tendency to over-compaction in the middle of the pavement and under-compaction close to the edges can be easily detected.

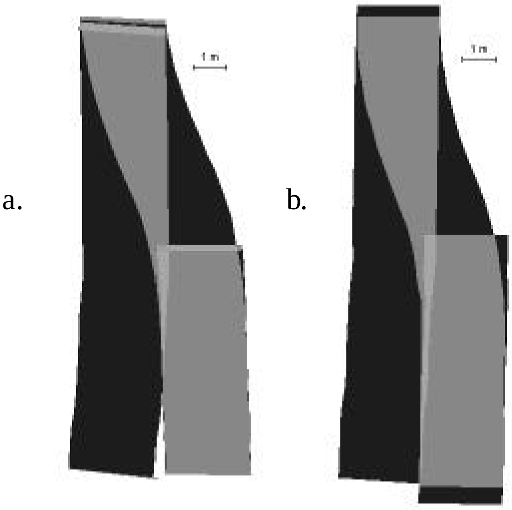

Figure 6: Pass maps observed in the experiment. a. Code - measured on-line based on code-differential processing, b. Phase – post-processed using phase observables

The comparison between the Code and the Phase results has brought the following results:

- The Code-DGPS modules estimate driving/stopped state and perform position, velocity, time (PVT) type filtering on their own. This has an effect of additionally smoothing the result. However, the movements at low speed (< 2 km/h) are filtered out. This effect can be observed on the Code pass map as an early stop condition, leading to an underestimation of the compacted surface. This effect is not critical in the practice, as the breaking/acceleration occurs with the vibration switched off and should not be counted as a valid pass.
- At the moment the absolute accuracy of the 2 Code DGPS system can be judged at about 80-90 cm, after removing an observed constant offset between the Code and Phase results. This is sufficient to obtain clear lanes in the pass map. However, longer tests are required to confirm this finding.
- The GPS signal reflections caused by the machine and mounting seem to have great impact on the multipath error and the final result. The validation on the target machine is necessary
- The performance of the filter with and without the articulation angle measurement was similar. For studied trajectories it is possible to remove it from the filter structure. However, due to varying width, this measurement is required for the machines with 2 articulation joints.

5. CONCLUSIONS

The presented positioning solution reaches good performance in static and dynamic mode. The pass maps obtained with the low-cost system are qualitatively very similar and allow for detection and correction of the major compaction errors identified by the experimental tests. Long term tests on the target machine are necessary in order to tune the filtering algorithms and fully asses the accuracy and robustness of the proposed solution.

The availability of suitable cost-effective and robust DGPS positioning solutions should improve the acceptance of compaction support systems in the near future.

The full scale tests of the presented algorithm are scheduled in Summer and Autumn 2002.

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