Georeferencing of condition information from railway infrastructure

Lars Johannes[1], Eduardo Almeida[1]

[1] German Aerospace Center
Institute of Transportation Systems
Lilienthalplatz 7, 38108 Braunschweig, Germany
Email: lars.johannes@dlr.de, eduardo.almeida@dlr.de

ABSTRACT

The condition-based preventive maintenance of the rail infrastructure shall reduce maintenance costs and increase the availability of the rail network in the future. In order to achieve this goal, the current condition of the tracks must be more frequently assessed as of today. This can be achieved, for example, with the deployment of autonomous sensor systems on regular rolling stock to perform measurements during commercial operation. In this scenario a precise and uniform georeferenced collection of condition data is needed for linking time-separated condition assessments and recognizing trends on the deterioration parameters. In this paper we present a modular and portable system for multi-sensor data acquisition on rail vehicles that can be used for train location as well as for condition assessment. Data from different relative and absolute sensors were acquired on a representative test site and combined for the calculation of the vehicle location. First results and analysis are included.

BIOGRAPHIES

Lars Johannes received his engineering diploma in surveying and mapping at the Technische Universität Berlin, Germany, in 2004. From September 2005 to May 2012, he was a research associate at the Institute of Geodesy and Photogrammetry, Technical University Braunschweig, Germany. In 2012 he defended his doctoral thesis. His current work at the Institute of Transportation Systems of the German Aerospace Center (DLR) focuses on the realtime positioning of trains and sensor integration.

Eduardo C. V. de Almeida received his engineering bachelor degree in Mechatronics at the University of Brasília (Brazil) in 2009 and his master's degree in Biomedical Engineering in 2012 at the University of Linköping (Sweden). Since January 2013 he works at the Institute of Transportation Systems of the German Aerospace Center (DLR) developing and integrating measurement systems for positioning and condition assessment on railway vehicles and for the research hi-rail vehicle RailDriVE®.

INTRODUCTION

The safe and cost-efficient maintenance of the railways presents a demanding challenge for infrastructure managers. While the increasing demand for track access creates the need for higher availability and higher operating grade, the increase of use further accelerates the infrastructure deterioration. The increased use on its turn increases the maintenance cost and reduces the availability due to unplanned interventions. Therefore, a solution to this conflicting scenario in the railway operation should address both the availability and the maintenance costs.

In this context, a condition-based preventive maintenance strategy promises to reduce maintenance costs and at the same time increase the availability of the rail network. The transition from predominantly corrective to preventive maintenance requires however a high awareness of the current condition as well as reliable predictions about the expected deterioration. To meet these requirements, the current condition of the tracks must be more frequently assessed as today. Furthermore, the relevant information from different sources (e.g. condition assessed with different measurement trains, track construction technology, track accumulated tonnage) must also be better correlated with each other to better orient maintenance decisions.

One promising approach to increase the frequency of condition assessment, is the use of autonomous sensor systems on regular vehicles. For linking information collected from different trains in space and time, a precise and uniform georeferenced collection of condition data is required. A flexible and yet cost-effective system capable of positioning the railway vehicles with track selectivity accuracy is needed. This system must be portable and possible to install within a few days on third party rolling stock (e. g. in the context of measurement campaigns on measurement vehicles of subcontractors) or be deployed for longer-term use on rolling stock in regular commercial operation.

For several years the positioning of railway vehicles has been an intensive research topic at the Institute of Transportation Systems from DLR where the hi-rail vehicle RailDriVE® serves as a mobile laboratory for the acquisition of sensor data [1] [2] [3] [4]. Based on these collected data, innovative algorithms are developed and tested under real conditions on the track. In our paper, we present a modular and portable system developed and tested on the RailDriVE® for multi-sensor data acquisition on rail vehicles. The system collects sensor data that can be used for train location as well as for condition assessment. This article focuses on the on the implementation and test of a positioning algorithm for railway vehicles bases on the Extended Kalman Filter (EKF).

PORTABLE SYSTEM

A measurement system to be deployed on regular operation trains must be compact, so that it can fit in limited spaces on a regular train. It must employ robust sensors and a robust computing unit in order to be able to operate at the rough railway environment e.g. sudden and extreme temperatures as well as pressure changes, dust, oil, snow and ballast. It must not interfere with pre-existing equipment and it must be compliant with relevant safety regulations. It must be cost efficient to allow deployment on multiple vehicles and it must operate autonomously and with minimal maintenance needs.

In order to address all of these requirements, the experiences acquired with the RailDriVE® were combined and pushed further. The basis for the sensor data acquisition is a successfully tested and platform independent modular software concept (Fig. 1) [5]. The sensor applications are responsible for receiving and parsing the incoming data and forwarding it to a software switch called Communication Central. This application distributes the sensor data to potential “users”, the logic applications, where data from one or more sensors are combined to extract relevant information e.g. sensor data fusion for positioning, detection of faulty conditions, map-matching. In addition, there are also applications that can trigger actuators or permanently emit status and position data to a central server.

This modular approach and separation between measurement and logic has proven to be of great value when adapting a system to attend different scenarios or requisites. It allows changes or substitutions on the sensor modules, as well as upgrades or modification on the logic applications without compromising other modules or the system operation. In a way, the system can be even up and down-scaled and tailored to attend different application scenarios.

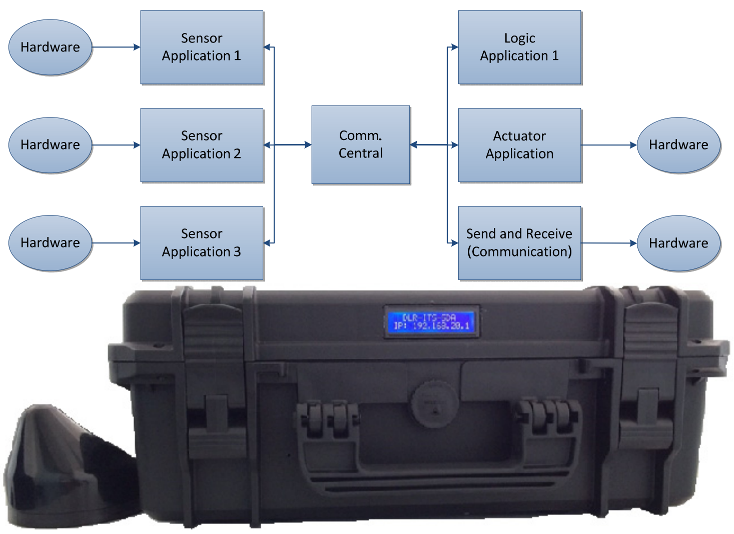

Fig. 1. Modular software concept (top) and portable measurement system (bottom).

Following the modular approach of the software, the hardware of the system was also designed to be modular and configurable. A railway certified (EN50155, EN50121) computer unit with multiple interfaces and swappable hard disks was chosen as the core of the system. The unit was complemented by a flexible power supply unit, which can accept a broad range and types of power input, as well as by an uninterruptible power supply (UPS). Furthermore, a multiband Antenna covering the LTE, UMTS, WLAN, GPS and GLONASS frequency bands was used for GNSS and data communication. The hardware was mounted on a frame and placed on a ruggedized portable case (Fig. 1).

In addition to the software environment, the system was also equipped with a set of self-monitoring routines that automates its operation and controls the measuring and communication modules. Periodic telegrams containing the actual position coordinates and status information are emitted to a central server, from where the units can be monitored. Large data amounts can be also transferred over WLAN to the server when the carrying vehicle stops at depots overnight. Furthermore the system can automatically download software updates.

TEST SITE IN BRAUNSCHWEIG, GERMANY

First measurements were performed on a test site in Braunschweig (Germany) where typical conditions were represented. Using the time from the positioning solution, the detected track defects could be accurately georeferenced. In addition to the accurate digital map of the test track, the position of the rail defects as well as their physical properties were accurately measured using a total station (Fig. 2). This information was digitally processed and made available for validation of the data obtained from the condition detection.

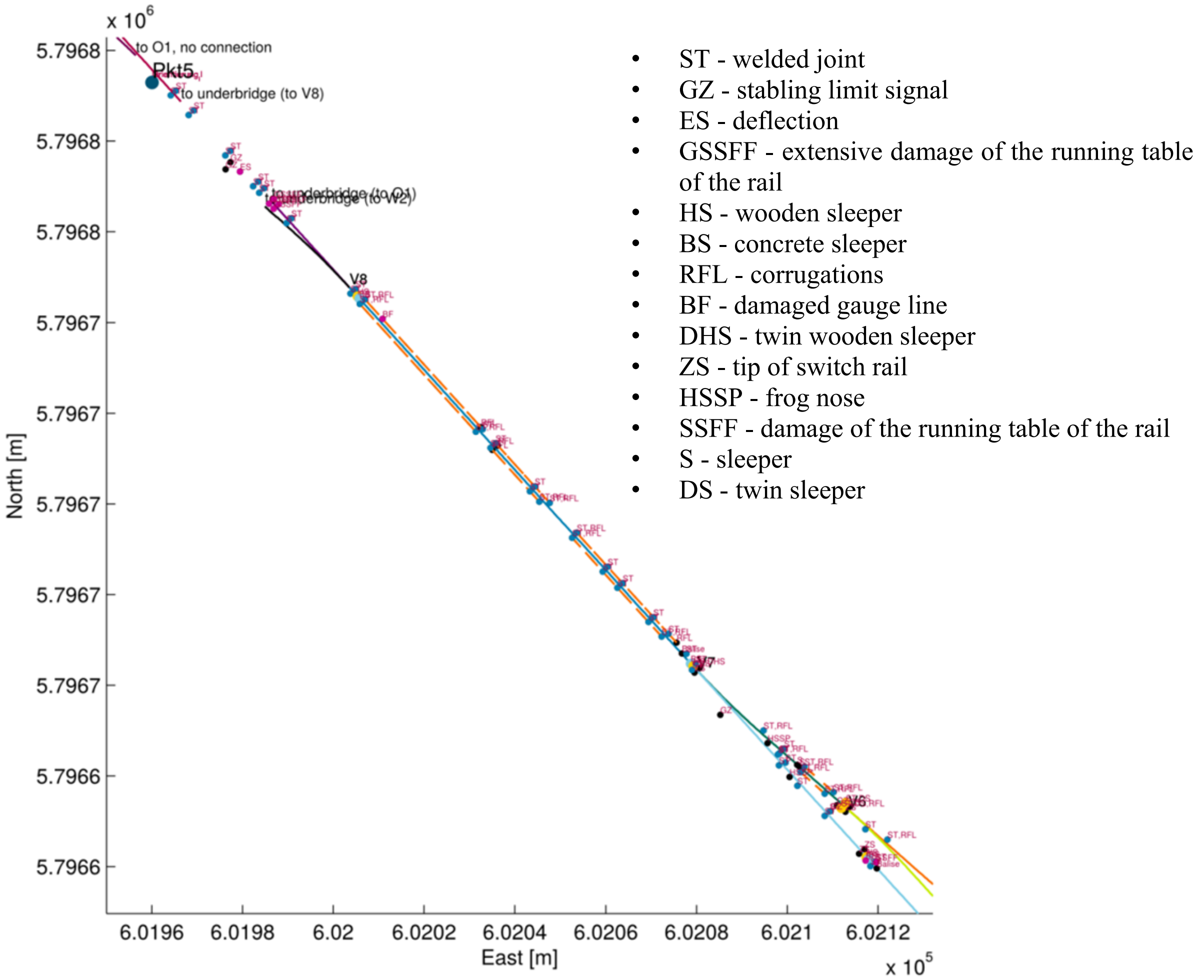

Fig. 2. Map of track conditions and characteristics.

A critical requirement for the positioning of railway vehicles is the track selectivity i.e. the location of a vehicle on the correct track. Track selectivity can be tested by driving over rail switches, since these are the only points where a rail vehicle can change tracks. Furthermore, since GNSS outages are relatively common on the railway environment, the positioning algorithm must attend the track selectivity requirement also when GNSS is not available. On the presented work, the RailDriVE® drove from the switch V8 over V7 and V6 (Fig. 2). A GNSS outage was provoked before V7 and until after V6.

FUSION OF RELATIVE AND ABSOLUTE SENSOR DATA

Data from standard relative and absolute sensors were combined for the calculation of the vehicle location on the tracks. These included a railway Doppler radar, an ETCS Balise reader, an inertial measurement unit (IMU) and the analysis of the carrier phase of a low-cost GNSS receiver. The data from the different sensors were stamped with a common accurate time basis. For the validation of the location information, the highly accurate digital map of the network was used. The fusion of the sensor data is done by means of an EKF. A *Constant Turn Rate and Velocity* (CTRV) model is the basis to describe the dynamic behaviour of the vehicle [6] and [7].

System Model

The complete state of the vehicle at time t is given by (Fig. 3):

$$\boldsymbol{x_t} = (\ x\ \ y\ \ \phi\ \ v_x\ \ \omega\ )^T\ .$$

Where:

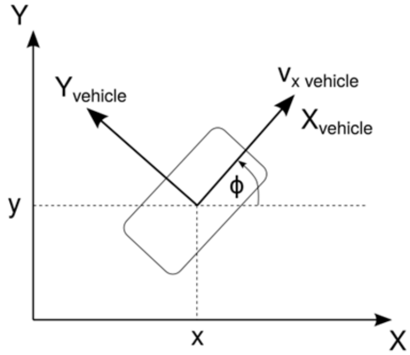

Fig. 3. System model variables.

x – easting position [m]
y – northing position [m]
ϕ – heading of the vehicle [rad]
v_x – velocity of the vehicle [m/s]
ω – yaw rate [rad/s]

The state can be transformed by the non-linear transition:

$$\boldsymbol{x_t} = \begin{pmatrix} \frac{v_x}{\omega}\sin(\omega T + \phi) - \frac{v_x}{\omega}\sin(\phi) + x_{t-1} \\ -\frac{v_x}{\omega}\cos(\omega T + \phi) + \frac{v_x}{\omega}\cos(\phi) + y_{t-1} \\ \omega T + \phi \\ v_x \\ \omega \end{pmatrix}.$$

They can be written in the compact form including the additive process noise $\boldsymbol{w}$

$$\boldsymbol{x_t} = \boldsymbol{f}(\boldsymbol{x}_{t-1}, T) + \boldsymbol{w}_t\ .$$

The process noise $\boldsymbol{w}$ is associated to the covariance matrix **Q.**

Measurement Model

Data from the different sensors form the observation vector:

$$\boldsymbol{z_t} = (\ x_{RTK}\ y_{RTK}\ x_{Balise}\ y_{Balise}\ v_x\ \omega)^T\ .$$

Where:

x_{RTK} – easting position of the RTK GNSS [m]
y_{RTK} – northing position of the RTK GNSS [m]
x_{Balise} – easting position of the balise [m]
y_{Balise} – northing position of the balise [m]
v_x – velocity of the vehicle [m/s]
ω – yaw rate [rad/s]

The measurement equations are defined as:

$$\boldsymbol{z_t} = \begin{pmatrix} x_t \\ y_t \\ x_t \\ y_t \\ v_x \\ \omega \end{pmatrix}.$$

The compact form, including measurement noise $\boldsymbol{v}$ follows:

$$\boldsymbol{z_t} = \boldsymbol{h}(\boldsymbol{x}_t) + \boldsymbol{v}_t \, .$$

As $\boldsymbol{v}_t$ is the observation noise and associated to matrix $\boldsymbol{R}$. The EKF steps in detail can be found in [8] and [9].

RESULTS

The data was collected by the hi-rail vehicle RailDriVE® on the test side in Braunschweig (Fig. 5). GNSS raw data was recorded with two low-cost receivers, a mobile and a reference station beside the track (Fig. 4). RTK positions were calculated by RTKLIB [10] using L1 carrier phase observations. In addition, an ETCS balise in the track bed was used to increase the position accuracy during GNSS outages and ensure track selectivity even at very low speeds (Fig. 5).

Fig. 4. Test site with GNSS reference station. The distance between the tracks is about 5 meters.

Fig. 5. Hi-rail vehicle RailDriVE® and a balise as track related infrastructure (yellow).

The performance testing of the EKF is shown on a track length of 209 meters (Fig. 6). Starting from the north-west, the GNSS system was switched off after 3.5 seconds for testing positioning calculation based on velocity and yaw rates only. Two changes in curvature occur during the test drive. At second 16.5 an ETCS balise was detected which increased position accuracy (orange point, Fig 7). One second later, the RTK measurements were available once again and guarantee high quality position results (Fig. 7, yellow points).

A system noise with zero mean was added to the velocity (σ_{v_x}= 0.004 m/s) and to the yaw rate (σ_ω= 0.002 rad/s). The measurement noise is assumed to be zero mean as well:

$$\boldsymbol{R_t} = \begin{pmatrix} \sigma^2_{x_{RTK}} & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_{y_{RTK}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{x_{Balise}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{y_{Balise}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{v_x} & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2_\omega \end{pmatrix} = \begin{pmatrix} 0.5^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.7^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.7^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.04^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.02^2 \end{pmatrix}.$$

With the help of a digital map, the velocity and yaw rates are sufficient sensor information to determine the travelled track. To minimize deviations across the driving direction a map matching step should be inserted after every update step of the EKF.

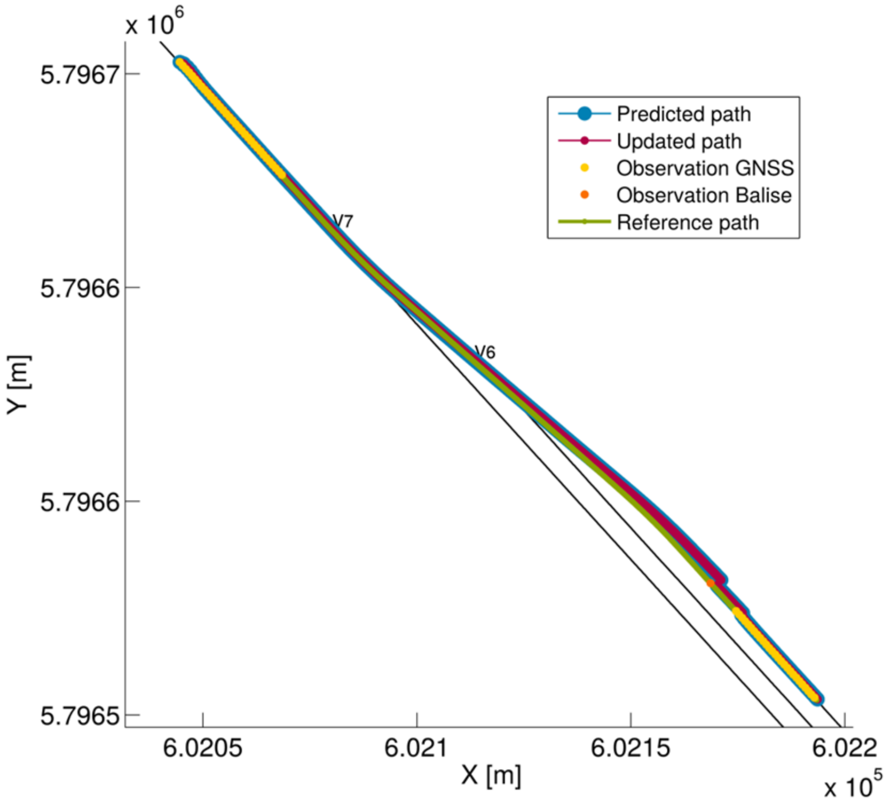

Fig. 6. Driven path, starting from the north-west and ending in the south-east (green points). Two changes in curvature occur to test the performance on a GNSS outage (missing yellow points in the middle of the track).

Over large areas with insufficient GNSS reception conditions, the balise coordinates (stored in a digital map) can be used to increase accuracy in driving direction (Fig. 7) and ensure track selectivity. Furthermore, detected curvatures might be used in the same manner. Also from Fig. 7, it can be observed that the filtered path after GNSS outage is slightly longer, which was be caused by the velocity sensor (Doppler radar). This path length is slowly corrected when GNSS positions are reintroduced.

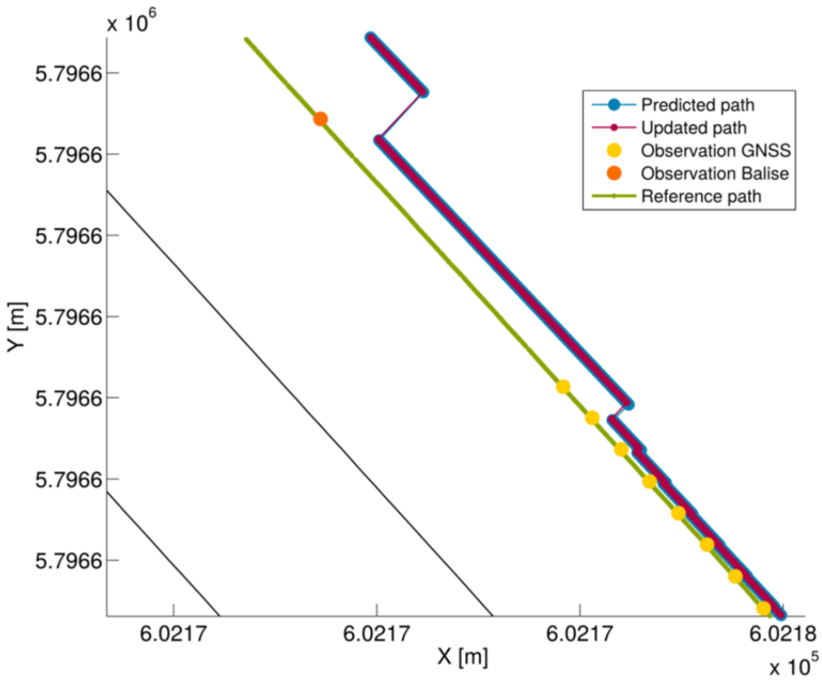

Fig. 7. The balise (orange point) increase position accuracy from around 2.3 meters down to 0.7 meter. When RTK samples are available, high quality positioning solutions are continuously available.

The curvatures changes on switch V7 (sec. 5 to 7) and after V6 (sec. 13 to 15) can be clearly distinguished in the orientation of the vehicle (Fig. 8). The transient on the first second of the test run, corresponds to the filter convergence to the absolute orientation.

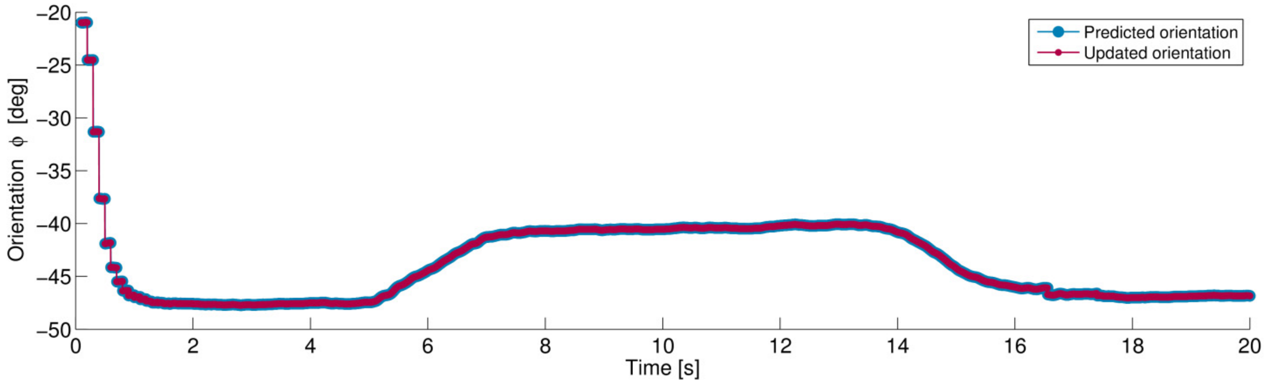

Fig. 8. Orientation of the vehicle. Both curvatures changes can be clearly observed as a change in the orientation. The initial change is caused by the initialization of the filter.

The velocity during the test drive was nearly constant (Fig 9).

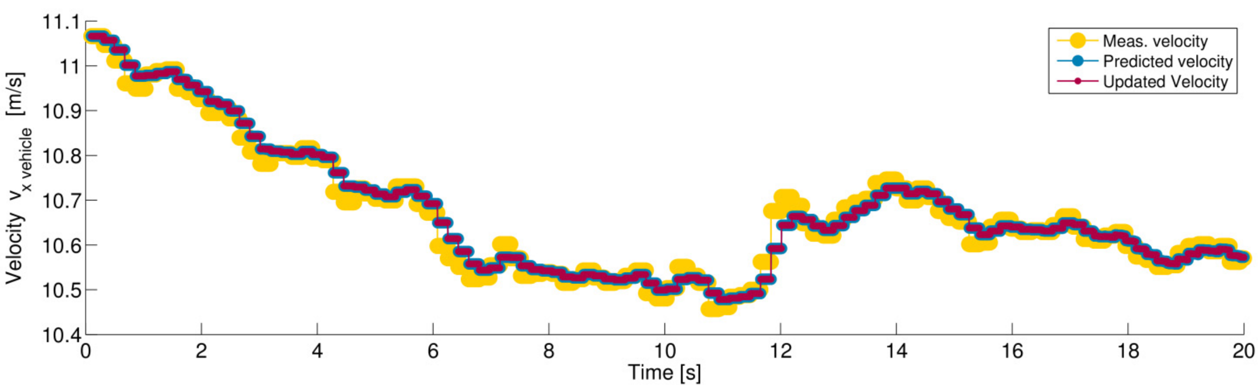

Fig 9. The velocity of the vehicle during the test was around 38 km/h.

Due to the velocity of about 38 km/h the gyro of the low-cost IMU was able to clearly turn out the both track curvature changes (on V7 and after V6) (Fig. 10).

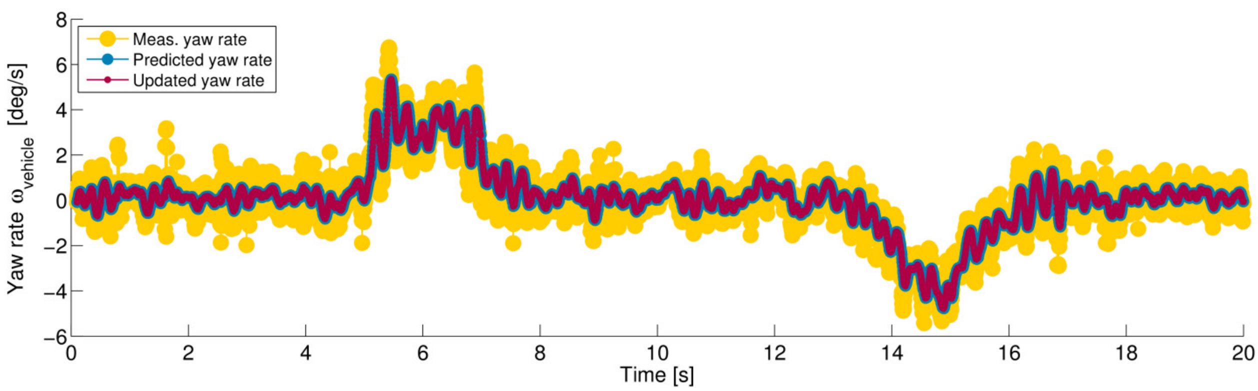

Fig. 10. The yaw rate changes by reaching and leaving of the both curvatures.

In Fig. 11, the estimated error of the EKF is shown. Due to the GNSS outage beginning at second 3.5 the position accuracy decreases up to 3 m, when at second 16.5 a balise is detected and the positioning accuracy is increased (first step down on the curve). The reintroduction of the RTK measurements (second step down at about 17.5 second) pushes the accuracy to under 0.4 m.

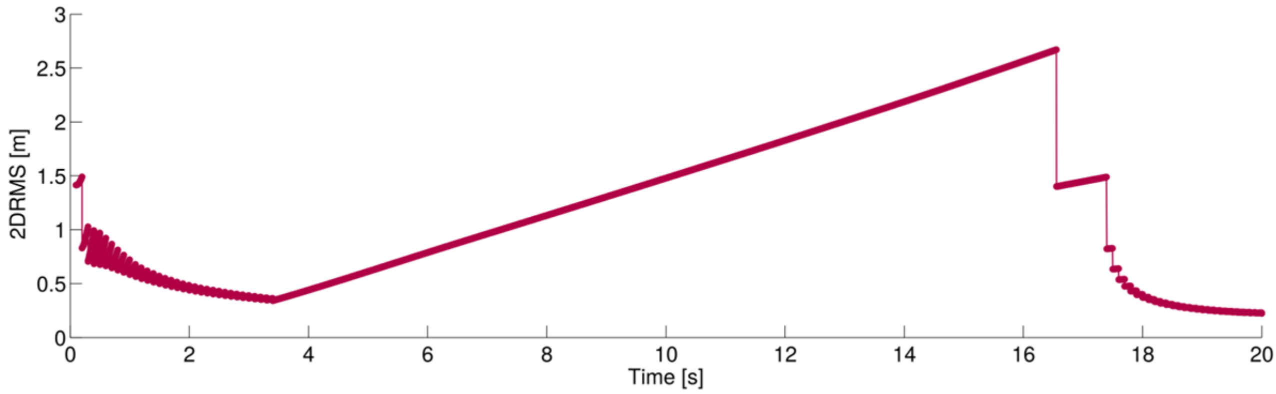

Fig. 11. 2D Root Mean Square Error (twice the distance RMS)

After an initial phase of around 1 second, the position accuracy increases below 0.5 meters. Because of GNSS-outage beginning at second 3.5, localization is done by velocity and yaw rate only. The accuracy decreases up to 3 meters. The balise and later RTK measurements increase the accuracy of the positions.

CONCLUSIONS

A robust estimation algorithm based on the EKF has been developed and obtained a reliable state vector of train position, orientation and velocity. The algorithm was tested with real data collected during a test drive with the hi-rail vehicle RailDriVE®. It included a railway Doppler radar, an ETCS Balise reader, a low-cost inertial measurement unit (IMU) and the analysis of the carrier phase of a low-cost GNSS receiver. The fusion takes the different sample rates and accuracies of the sensor data into account.

The result shows that the driven track with its curvatures can be determined by means of velocity and yaw rate measurements only. The localization results can be used to geo-reference track condition from sensor readings like accelerations. Further tests with lower driving velocities will be performed to further investigate the filter robustness. Moreover, an extended sensor calibration should increase the accuracy of the relative sensors in case of insufficient GNSS reception for longer periods. At last a map matching step after every EKF update should be included to produce positions that always lay on the tracks and can be directly used to investigate degradations over time.

REFERENCES

[1] K. Gerlach and C. Rahmig, "Multi-hypothesis Based Map-matching Algorithm for Precise Train Positioning," *12th International Conference on Information Fusion,* July 2009.

[2] K. Lüddecke and C. Rahmig, "Evaluating Multiple GNSS Data in a Multi-Hypothesis Based Map-Matching Algorithm for Train Positioning," *IEEE Intelligent Vehicles Symposium,* June 2011.

[3] C. Rahmig and K. Lüddecke, "An IMU as the basic vehicle-borne sensor within a modified Multi-Hypothesis Based Map-Matching Algorithm for Train Positioning," *European Navigation Conference 2011,* Dec. 2011.

[4] C. Rahmig and K. Lüddecke, "Tunnels and Bridges as Observable Landmarks within a Modified Multi-Hypothesis Based Map-Matching Algorithm for Train Positioning," *European Navigation Conference,* April 2012.

[5] E. C. V. Almeida, L. Johannes and J. C. Groos, "TrackScan -TrackScan - A portable System for Georeferencing Conditon Measurements of the Railway Infrastructure," *DGON POSNAV,* Nov. 2014.

[6] S. S. Blackman and R. Popoli, Design and Analysis of Modern Tracking Systems., Artech House, 1999.

[7] R. Schubert, E. Richter and G. Wanielik, "Comparison and Evaluation of Advanced Motion Models for Vehicle Tracking," *The 11th International Conference on Information Fusion,* July 2008.

[8] G. Welch and G. Bishop, "An Introduction to the Kalman Filter," *UNC-Chapel Hill, TR 95-041,* 24 July 2006.

[9] Y. Bar-Shalom, X. Rong Li and T. Kirubarajan, Estimation with Applications To Tracking and Navigation, New York: John Wiley & Sons, INC., 2001.

[10] T. Takasu, "An Open Source Program Package for GNSS Positioning," [Online]. Available: http://www.rtklib.com/. [Accessed 28 03 2015].