Train-Localization in Tunnels using Magnetic Signatures

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***Abstract*— This paper describes the results of a measurement campaign with a localization system for rail vehicles, which was significantly improved by integrating a novel passive magnetic field-based position and velocity measurement method in combination with a learnable digital map and conventional, on-board-only sensors such as inertial sensing and GNSS.**

***Keyword*— magnetic signature, magnetometer, localization, tunnel, train, TrainCAS**

I. INTRODUCTION AND BACKGROUND

The automation of rail traffic requires, next to digitization of the infrastructure, the digitization of the vehicle side. In particular, a precise and reliable localization of vehicles is essential in order to always be able to control the traffic flow on the basis of a complete situation representation and to react quickly to disruptions. The need for a higher degree of automation is well motivated by the number of overrun stop signals (signal passed at danger, SPAD) and collisions between rail vehicles. The number of SPADs is an important safety indicator and can be seen as a precursor to accidents. The German Federal Railway Authority's report for Germany for 2017 shows that the number of SPADs has continued to increase each year since 2014. The situation is similar across Europe and internationally. For example, the European Rail Safety Report 2010 lists 300 to 673 collisions between trains in Europe p.a. for previous years, i.e. 1-2 collisions in Europe per day on statistical average.

These accidents - like various others - could have been prevented with an innovative collision warning system based solely on the trains' equipment. This collision warning system, developed jointly by the German Aerospace Center (DLR) and its spin-off Intelligence on Wheels (IoW), brings the TCAS/ADS-B approach known from aviation to rail, where such safety technology based on the principle of a "safety overlay system" was previously unknown. Unlike traditional available technology for technical train protection, the system is not dependent on the rail infrastructure. The technology can therefore be implemented very cost-effectively and easily retrofitted into existing vehicles. The core of the operating principle is a regular exchange of relevant information, including position, direction of travel and speed, between rail vehicles equipped with the system via direct, basestation-less train-to-train radio communication. The vehicle unit installed in each rail vehicle continuously evaluates the traffic situation and alerts a critical situation to the driver by means of acoustic and visual warning signals. The warning levels can be parameterized. They are defined in such a way that the trains can be brought to a standstill in good time if there is a risk of collision. In the basic version, the system does not intervene directly with the train control system in the event of an alarm, but is operated as a driver assistance system where the driver remains in control.

The collision warning system (product name "TrainCAS") has been successfully launched on the market in 2013. Its core is a localization unit consisting of inertial and magnetic sensors, a satellite navigation receiver (GNSS) as well as a digital route map. The availability and quality of the positioning solution is very good in major parts along the track, especially for protecting vehicles on the open track between stations. On average, availability and accuracy are also sufficient for positioning under many difficult environmental conditions. However, in selected difficult sections, the localization performance is not optimal. This is sometimes the case in the vicinity of stations, in shunting areas, or in long straight tunnels.

Fig. 1. GNSS Receivers as well as inertial sensors face their limits in tunnels, whereas the earth's magnetic field remains an excellent source of signal.

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Earlier research findings of DLR showed that in particular the problem of long tunnels can be solved almost completely by integrating magnetic field sensors. In the general approach, location-dependent influences of the rail infrastructure on the earth's magnetic field - so-called magnetic field signatures - are measured during a journey and compared to the magnetic field data stored in a digital map. This makes it possible to determine position and speed even in places where, for example, GNSS signals can only be received with interference or not at all and the inertial sensor signatures cannot be clearly assigned to a straight section of track as illustrated in Fig. *1*.

To verify this thesis, corresponding algorithms were prototypically implemented and tested with a research train from Deutsche Bahn (see Fig. *2*) on various tracks in Germany during a measurement campaign lasting two weeks [2]. This paper focuses in particular on the findings from driving through many tunnels, some of them very long, on the high-speed line between Kassel and Göttingen, showing also original results not previously published in section IV.

Fig. 2. Deutsche Bahn's "advanced TrainLab".

II. THE MEASUREMENT CAMPAIGN

A. Setup

Several magnetic field sensor arrays were built and used for the project and the measurement campaign. A sensor array comprises several elements with similar magnetic field sensors. Additional sensors were in use providing a reference.

Two different kind of sensor array elements were in use: The array element type "Xsens" and array element type "DLR". Both types comprised of components available on the market with standard electrical interfaces and well known behavior including in the field of railways. The main objective was to evaluate the performance limits of the magnetic localization, not to develop new sensors as e.g. [7].

The CAN bus was selected for data communication with the sensors. The CAN bus has several advantages: First of all it is an established bus system in vehicle construction for decades and is robust against electromagnetic interference, which can typically occur in vehicles. The CAN bus allows for an expandable architecture of the sensor arrays with additional elements. Since it is a bus communication, only one line is needed for all elements. Furthermore, there are many components on the market that work with the CAN bus (microcontrollers, sensors, USB interfaces for PC, reference implementations). The small payload of the CAN messages with 8 bytes proved to be a disadvantage. Simultaneous measurements of a sensor had to be distributed over several messages. Another disadvantage is the net bandwidth of the data transmission due to the high telegram overhead. The maximum bus data rate of 1 Mbit allows approx. 8500 messages per second and thus a data transmission of less than 70 kB/s. In practice, many components and implementations cannot cope with the highest bus speed simultaneously to highest bus load and thus regularly lose messages. The sensor elements therefore operated at a reduced bus speed for mostly error-free transmission.

Time synchronization of the sensor elements is important for the analysis of disturbances and stationary signal components of the magnetic field, the comparison of different measurement positions and the velocity measurements. The clock and timing controller included a GNSS receiver and a microcontroller with CAN interface. The GPS time and the GPS PPS (pulse per second) clock are used for time synchronization. The GPS time is written every second from the microcontroller to the CAN bus. The PPS clock is converted to a differential signal by an RS485 interface driver and provided to the sensor elements on the array cable. Each sensor element receives this clock and can thus realize its own time synchronization.

B. Sensor Element "Xsens"

The "Xsens" sensor element contains an inertial and magnetic field sensor from the company Xsens. The sensor has several interfaces, including a CAN bus interface. This sensor was installed on a printed circuit board in an aluminum housing. A printed circuit board was made to connect the sensor mechanically to the housing and electrically to the array cable via terminals. The terminals were doubled, so that another sensor can be attached to each element in series. The cables are equipped with M12 plugs and sockets, so cables of different lengths certified for railroad use can be connected between the sensors.

Each Xsens sensor allows time synchronization of the inertial data. The clocks for the sampling times can be started together with an external signal. Regular signals are used to correct drifting of the clocks. The magnetic field data is output in the same time raster of the inertial data, but with a maximum of 100 Hz. With higher sampling rates it has been shown that there are repetitions of the respective last, current value.

C. Sensor Element "DLR"

The "DLR" sensor elements were built on a specially developed circuit board with individual electronic components. The main components are a microcontroller, a magnetic field sensor as well as interface driver components and voltage converters. Fig. *3* shows the opened array element with the printed circuit board and the microcontroller in the center of the image. The magnetic field sensor is an integrated chip sensor from Kionix with a size of 3x3 mm. The sensor can be seen at the upper end of the printed circuit board. The microcontroller is the link between the CAN bus and the sensor.

The time synchronization is done using the PPS clock, the GPS time and the internal clock of the microcontroller. The magnetic field sensor is an integrated system with the elementary sensors, measuring bridges, A/D converter, digital interface (I²C) and a controller. The magnetic field sensor works with its own internal clock. It is not possible to control the exact measuring time from outside. Only the last measured value is provided via the sensor's interface. The measurements can nevertheless be attributed to a specific point in time through a signal which always becomes active as soon as a new measurement is available. From the CAN messages, the absolute time from the clock and time element can be merged with the measured values and the fraction of a time unit in a further step of the data processing.

Fig. 3. Sensor element "DLR".

One array with eleven such elements already existed prior to the project ("DLR-1"), the second array ("DLR-2") with ten sensor elements was built after a revision of the printed circuit board. The DLR-2 array consisted of five indoor sensor elements and five outdoor sensor elements on a steel frame mounted under the train as illustrated in Fig. *4*.

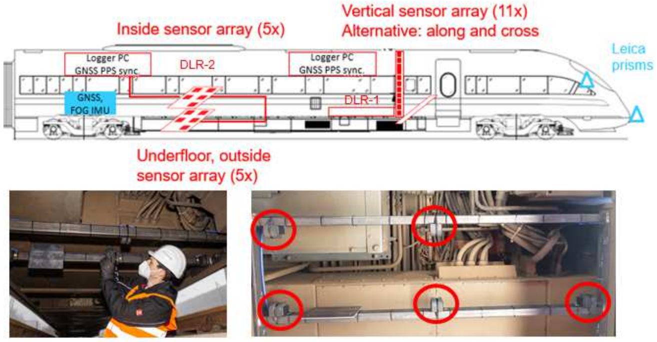

Fig. 4. Measurement setup on one compartment of DB‘s advanced TrainLab.

III. MAGNETIC FIELD BASED LOCALIZATION

A. *Measurements*

The measurements were carried out in a time window of just under 14 days on various routes, including Berlin, between Göttingen and Kassel, and in Munich and Augsburg [2]. The measurement scenarios covered typical railroad scenarios as well as particularly critical scenarios for magnetic field-based train localization. In addition, various measurement positions on the train itself were tested.

The tunnel runs in focus in this paper took place on the high-speed line between Göttingen and Kassel-Wilhelmshöhe as illustrated in Fig. *5*. Four “shuttle” runs were performed on the entire route section, as well as shorter shuttle run between Göttingen and Jühnde. Speeds of up to 200 km/h were reached during these measurements.

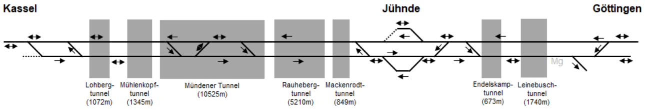

Fig. 5. Topographic illustration of the track network between Göttingen and Kassel inside and outside the tunnels. Arrows indicate the availability of data from directional runs.

The journeys took place at night, as there is a too dense frequency of regular high-speed trains during the day. Noteworthy, track changes in the tunnel to the opposite track took place. In selected areas the reference position of the train was determined with a laser tachymeter up to several hundred meters into the tunnels (see photo in Fig. *6*). Emergency braking with the magnetic rail brake was initiated from full speed during one of these shuttles. The section of the high-speed line between Göttingen and Kassel-Wilhelmshöhe is about 45 km long and encompasses seven tunnels with a combined length of over 21 km, including the Mündener Tunnel, which is 10,525 m long.

Fig. 6. Tunnel runs with position reference measurements through the tunnel entrance. The Laser tachymeter is shown in the center of the picture to the right of the track.

For data analysis, the time-stamped magnetic field measurement data was first transformed from the time domain to the spatial domain using the recorded velocity and reference position. As a result, the location-dependent magnetic field signatures along the track are obtained.

B. *Distortions of the magnetic field*

The measured magnetic field signatures significantly depend on the environment. The local geomagnetic field along the tracks is influenced by ferromagnetic materials such as the rails themselves, their fastenings, reinforcements in sleepers, catenary poles, noise barriers and reinforced concrete structures such as platforms, bridges, underpasses, buildings etc. Here, so-called hard and soft magnetic effects cause the earth's magnetic field to be "distorted" locally in the area around these elements, i.e. to vary in intensity and direction. These variations can be very different depending on the environment, e.g. urban, suburban or rural.

Fig. *7* shows an excerpt of the measurements on the high-speed line Kassel-Göttingen. The figure shows the magnetic flux density measured and normalized to the magnitude of the earth's magnetic field in the direction of travel of the first sensor of the Xsens array (X1) in car 605.2 from a total of 4 runs on the directional track to Göttingen at speeds of up to 200 km/h. The figure shows that the local variations are generally very repeatable, although the track section considered is in a rural environment with fields and forest and therefore the variations are relatively small in the range of a few percent of the nominal geomagnetic field. At about 8 km of relative distance, clearly stronger fluctuations are recognizable, exactly at the point where the route passes over a highway. The fluctuations amount to about 40-50% of the nominal field strength. Here it becomes clear that constructions like bridges can lead to clearly pronounced signatures, as they are often observed especially in the measured data in suburban and urban environments.

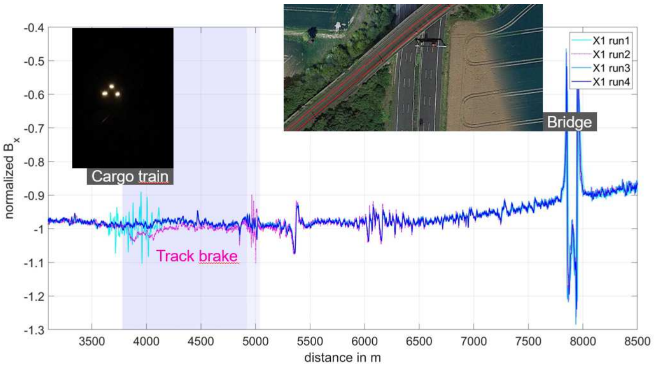

Fig. 7. Excerpt of magnetic field data of 4 runs on the same track in the same direction from Kassel to Göttingen.

However, the first two runs in Fig. 7 also reveal disturbances in the range between 3.5 and 5 km relative distance. The deviations of the first run were caused by a crossing freight train, as could be proven despite darkness on the basis of the recordings of the video cameras in the driver's cabins. Not completely surprisingly, a larger deviation of the signature during the braking maneuver can also be observed when using a magnetic rail brake. Interestingly, the effect could be measured to persist over a period of several hours. These remarkable findings were published in [3].

C. *Localization based on magnetic field signatures*

The position of the train is determined from the position on the reference signature where there is the greatest similarity between the test signature and the section of the reference signature of the same length [6]. The test signature is a short section of a measurement run, whereas the reference signature is a long section or the complete signature of another measurement run. In the implementation of real-time train localization, the reference signature is the signature that is read from the map and is known beforehand. The test signature is the currently measured signature. For each possible path through the topology, there is one reference signature in the map for this purpose. The mapping of magnetic field signatures is done from measurements. For this, magnetic field measurements are recorded together with other measurements such as GNSS position and velocity measurements, odometry, and inertial measurements in the train coordinate system. These measurements can then be used to either generate a new map or to add specific track information to an existing map including calibration [1][4]. The latter option requires an existing initial map such as the one already in use in the TrainCAS system. The mapping is processed after the measurements have been recorded before it can be used (post-processing).

D. *Accuracy of magnetic field based localization*

To illustrate the accuracy of the achievable along track localization results based solely on magnetic field signatures, a cumulative error distribution is shown in Fig. 8. For each test signature, there is an associated GNSS position that can be assigned to the data using a time stamp. The localization result determines the most likely position of the test signature on the reference signature. There are also associated GNSS positions for the reference signature. The measurement errors are determined from the distance of the associated GNSS positions between the determined position on the reference signature and the test signature. The test signatures were evaluated non-overlapping and systematically every 50m with signature lengths of 50m. The evaluation was performed with measurement data at the Berlin Südring. Post-processed data from a geodetic reference receiver (Septentrio PolaRx5) with correction data was used as position reference. The determined measurement errors are close to the range of GNSS accuracies. The achievable accuracy also depends on the mounting position of the sensors on the vehicle. The accuracy marked in Fig. 8 is the error value in the direction of travel, below which 95% of all errors lie. The accuracy of the longitudinal positioning is 1.8m for the inner sensors, and 1.5m for the outer sensors. Details of this evaluation have been published in [5].

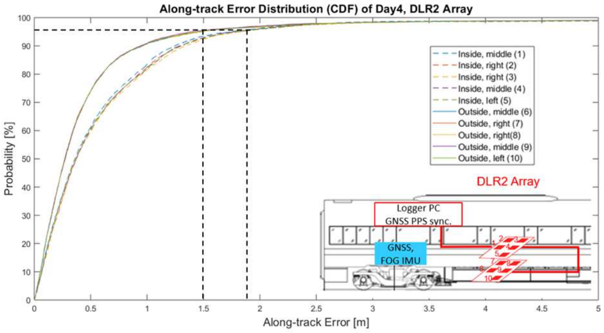

Fig. 8. Accuracy of magnetic field based localization achievable using different sensor positions on the train (using array DLR-2).

The evaluation of the sensor offset in the cross direction has shown that even with an offset from one rail head to the other rail head, the signatures differ significantly and show only few similarities. This comparatively strong signature change in the cross direction can be profitably used to identify the correct track in the case of sensors placed in the center of the vehicle.

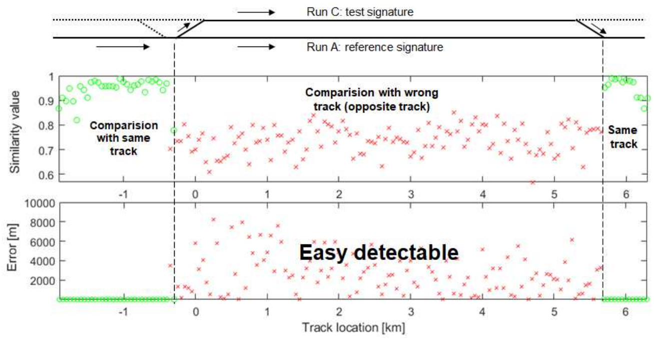

Fig. 9. Similarity values on the same vs. the parallel track between test and reference signature.

Fig. *9* shows an example of a reference run on a directional track. The test run changes to the parallel track at a switch and returns to the directional track at the next switch after a while. The track is recognized by analyzing the different path hypotheses, i.e. by identifying the "better" matching track.

E. *Magnetic field based localization inside tunnels*

The most commonly used option for localization within a tunnel of limited length is relative localization from an absolute location outside the tunnel using speed or distance measurements via dead reckoning with odometry or inertial sensor technology. Short tunnels are traversed in a relatively short time. Depending on the method, the duration of the passage and the quality of the path measurement are decisive for sufficient localization quality. Requirements for sufficient localization in the tunnel also depend on necessities, such as a required positioning accuracy before a stop signal or a switch in or shortly after the tunnel. If the type of application does not require real-time capability, then the first absolute localization after a tunnel can also be used for a correction of the relative path measurement.

Magnetic field-based localization is therefore particularly interesting in tunnels, since on the one hand GNSS does not provide a position there due to signal shadowing and on the other hand, as shown above, the accuracy of magnetic field-based longitudinal localization does not degrade over the length. Fig. *10* shows three different magnetic field signatures of three passings of the same track in the same direction in the axes X,Y,Z over 2 km within the Mündener tunnel. The strong similarity of the signatures at the same locations is evident - the three signals per axis overlap and can hardly be differentiated visually. The sensor in use here was mounted outdoor.

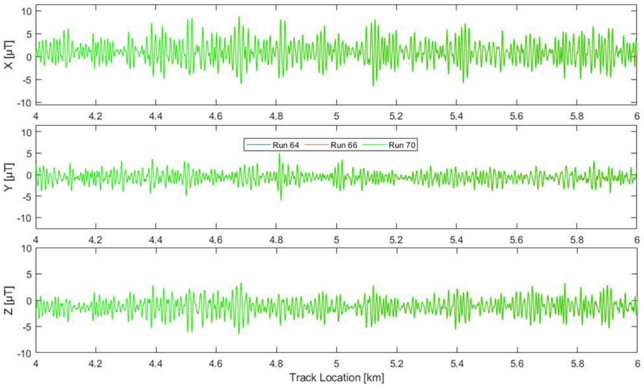

Fig. 10. Magnetic signatures of three different runs over 2 km of the Mündener tunnel are hardly separable.

Magnetic field localization works equally well inside and outside the tunnel: parallel tracks and switch paths can be distinguished. Localization works with the exception of interference from other trains as revealed in Fig. *11*.

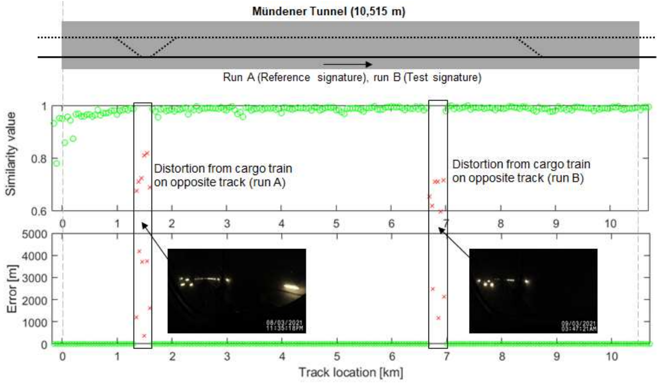

Fig. 11. Localization inside Mündener tunnel with two distortions by freight trains.

IV. INTEGRATED LOCALIZATION

Magnetic field localization provides the greatest added value in situations where the reception of satellite navigation signals is disrupted or not possible at all. The integrated localization therefore focuses on this scenario. Fig. 12 shows the speed measurement results of the previous TrainCAS system compared to the solution with additionally integrated magnetic field localization. The difference is clearly visible in the area of the 1740m long Leinebusch tunnel on the Kassel-Göttingen line: While updating the position inside the tunnel without GNSS by means of IMU and map leads to larger deviations from about halfway through the tunnel, the integrated solution follows the actual course very well. The recordings of the RTK receiver as well as the wheel odometry of the measurement train in the tunnel during the measurement campaign were used as position and speed reference for this evaluation.

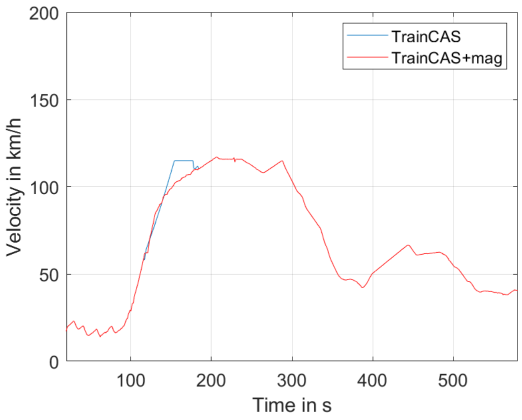

Fig. 12. Comparison of the speed estimation inside the Leinbusch tunnel on the line between Göttingen and Kassel, with and without magnetic field localization integrated.

The difference gets particularly obvious in the longitudinal positioning error of the two solutions, as can be seen in Fig. 13. In this example, the position update using IMU and map without magnetic signatures leads to errors of more than 90 m, while the error with integrated magnetic field localization remains limited to about 20 m along the entire tunnel - far below corresponding limits on high-speed lines.

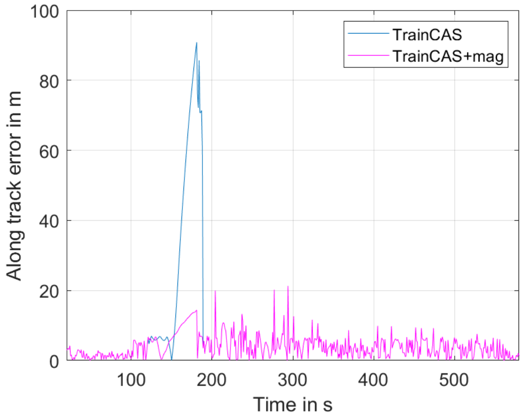

Fig. 13. Comparison of the positioning error, with and without magnetic field localization integrated.

V. CONCLUSIONS

The measurement campaign and its subsequent evaluation has shown impressive results and findings for magnetic field-based localization. The results of the campaign provide good indicators where and at what distance to place magnetic sensors at the train to achieve the best results in a product setup as a feasible trade-off between installation& management cost, interference with other systems of the train and signature stability. The localization accuracy in longitudinal direction is comparable to that of GNSS (1.5 m sensor outside train; 1.8 m sensor inside train). Due to track selectivity, it is possible to identify the correct track and a track change at a switch. Trains in the surrounding area (e.g. on the opposite track) cause distortions, but these can be easily detected and handled with error correction. Magnetic field-based localization has particular strengths in long tunnels and outperforms any other train autonomous localization system in most challenging environments. The performance of the overall system improves significantly by integrating the magnetic field localization into the localization fusion, as could be shown with the example of TrainCAS. Here the correct track could be identified at any time between the switches (no cross-track error) and the longitudinal localization error could be kept below 20m along the entire track, even in tunnels longer than 10 km. Speed error was below 1.7 km/h (RMSE) with support of magnetic signatures.

REFERENCES

[1] Siebler, Benjamin und Lehner, Andreas und Sand, Stephan und Hanebeck, Uwe D. (2021) “Evaluation of Simultaneous Localization and Calibration of a Train Mounted Magnetometer”. ION GNSS+ 2021, 20.-24. Sep. 2021, St. Louis, USA.

[2] Sand, Stephan et. al. (2021) “Radio Interference Measurements for Urban Cooperative Intelligent Transportation Systems”. In: 94th IEEE Vehicular Technology Conference, VTC 2021-Fall. IEEE. 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), 27-30 Sep 2021, Online Only. doi: 10.1109/VTC2021-Fall52928.2021.9625167. ISBN 978- 166541368-8. ISSN 1550-2252.

[3] Lehner, A. et.al. (2022) “Impact of Track Brakes on Magnetic Signatures for Localization of Trains”. Fifth International Conference on Railway Technology: Research, Development and Maintenance 2022, 22.-25. Aug. 2022, Montpellier, France.

[4] Siebler, Benjamin und Lehner, Andreas und Sand, Stephan und Hanebeck, Uwe D. (2023) “Simultaneous Localization and Calibration (SLAC) Methods for a Train mounted Magnetometer”. Navigation, Journal of the Institute of Navigation. The Institute of Navigation Inc. ISSN 2161-4296.

[5] Heirich, Oliver und Siebler, Benjamin und Lehner, Andreas und Strang, Thomas und Sand, Stephan (2022) “Magnetic Train Localization: High-Speed and Tunnel, Experiment and Evaluation”. ION GNSS+ Conference 2022, 21.-23.Sept.2022, Denver CO, USA.

[6] Siebler, Benjamin und Heirich, Oliver und Lehner, Andreas und Sand, Stephan und Hanebeck, Uwe D. (2022) “Robust Particle Filter for Magnetic Field-based Train Localization”. International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+), 19.-23. September 2022, Denver, USA.

[7] KIT/Bosch press release 079/2022 (2022), “New Sensor to Increase the Number of Trains on the Route”, https://www.kit.edu/kit/english/pi_2022_079_new-sensor-to-increase-the-number-of-trains-on-the-route.php