Magnetic Train Localization: High-Speed and Tunnel, Experiment and Evaluation

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BIOGRAPHY

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Thomas Strang received his Ph.D. from University of Munich in 2004. Since 2000 he is researcher at DLR focusing on Communications and Navigation in Transport as well as Cyber Security. Thomas has authored and co-authored more than 100 publications, some of them cited more than 2000 times, and co-founded Intelligence on Wheels GmbH.

Stephan Sand received his Ph.D. from ETH Zurich, Switzerland in 2010. Since 2002 Stephan has researched wireless communications and multi-sensor navigation at DLR. Since 2014 he is leading the Vehicular Applications Group researching robust navigation and wireless communications technologies for road users and railways. Stephan has authored and co-authored more than 100 publications.

ABSTRACT

Magnetic train localization uses the characteristic distortions of the Earth magnetic field from the railway tracks. The magnetic train localization is able to identify the correct track and can solve an along-track location on the tracks. In contrast to GNSS, the magnetic train localization works in tunnels. In order to prove the practicality of the magnetic train localization method, a comprehensive train experiment has been conducted. Therefore, a high-speed train has been equipped with 28 magnetic and reference sensors such as wheel odometer, GNSS and inertial sensors. Measurements have been recorded in urban, high-speed and tunnel scenarios over $2200\,\mathrm{km}$ in eight measurement days. This paper describes briefly the measurement setup, the research questions, the experiment scenarios, the evaluation method and first results and findings.

I. INTRODUCTION

Railways is seen as an environmentally friendly way of mass transportation with a low greenhouse gas footprint. Current efforts towards climate neutrality puts the railway transportation of passengers and cargo into focus. Europe's high-speed services are advancing and get more and more competitive in national travels compared to aircraft in terms of total travel time. The goal of an advancing railway traffic is a more efficient use of the track resource with same or higher safety at the same time. There are many new ideas of advanced railway applications and also ideas for further automation towards autonomy.

The topic of train localization based on onboard sensors is currently gaining more and more attention by large railway service and infrastructure operators (German DB, French SNCF, Swiss SBB, see EUSPA (2022)), politics and railway suppliers across Europe. State-of-the-art train control relies on elements in the infrastructure and also on equipment on the train. This causes high costs and the infrastructure and the onboard system requires maintenance. In contrast, an onboard train localization uses only onboard sensors and a digital map of the tracks. This approach is similar to the current developments in the automotive domain. Nevertheless, there are some differences in the railway domain. The main requirement is a track-selective localization.

In case of switch, station or a line with parallel tracks, the correct track with the train must be identified. GNSS is one of the prime sensors considered for an onboard train localization. There are current research projects ongoing from EU, GSA, and national programs that focus on a safe and certifiable train localization with GNSS. Despite the benefits of GNSS for train localization, GNSS alone is not sufficient for all scenarios in terms of accuracy and availability. The railway environment causes often multi-path, intended or unintended jamming with privacy protectors, and especially tunnels are a problem.

Since several years, our research group investigates in a method called magnetic train localization or magnetic field-based train localization Heirich et al. (2017), Heirich et al. (2020), Siebler et al. (2020), Heirich and Siebler (2017), Siebler et al. (2018), Siebler et al. (2017), and Lehner et al. (2022). The magnetic train localization relies on the many ferromagnetic objects in the railway environment. It is difficult to find the north direction with a magnetic compass on rails due to disturbances caused by the rails and other ferromagnetic objects. Nevertheless, these disturbances depend on the location and can be measured repeatedly. Other locations show different magnetic disturbances. In terms of magnetic train localization, these disturbances create a useful signal for localization over the course of the track. This signal is called magnetic signature. A magnetic signature contains up to three magnetic signals (X,Y,Z axes) over a 1-D track location.

II. USE-CASES OF MAGNETIC SIGNATURES IN TRAIN LOCALIZATION

There are three different use-cases for train navigation based on magnetic sensor data: absolute train localization, relative train localization and train odometry.

1. Absolute Train Localization

A digital track map stores magnetic signatures of the tracks. A train is equipped with one or more magnetic sensor. There are two approaches investigated by our group: a particle filter approach Siebler et al. (2020), and a signature similarity approach Heirich and Siebler (2017). The signature similarity approach is similar to fingerprinting and explained shortly: The time dependent samples are transformed to spatial samples with speed information and filtered afterwards. This creates a current signature measured by the train. The current signature is then compared to all possible map locations with a similarity measure. The location with the highest similarity is selected as output. For further robustness, a method evaluates certain quality metrics in order to identify and suppress a wrong location output.

2. Relative Train Localization

The second use-case is the relative train localization on tracks Heirich and Siebler (2017). There, the distance on tracks is estimated between to locations. These locations can be the tail and tip of two trains that run consecutively, or the train-front and the train-end in order to monitor the train integrity. The method works as follows: The first train records a signature and the subsequent train compares its signature to the first signature. Since the signature is the magnetic signal over distance. The lag, or shift, of these signatures show directly the distance on tracks. This method does not require a map. Other distance methods, such as optical or radio ranging, measure a direct, line-of-sight distance.

3. Train Odometry

The last application is the magnetic train odometry, also used in Siebler et al. (2017). Two magnetometers measure the magnetic signals in a known distance. A method evaluates the time-shift and the speed is computed in combination with the known distance. This method does not require a map.

III. RESEARCH QUESTIONS FOR TRAIN EXPERIMENT

This paper presents results from a comprehensive measurement campaign with a high-speed train for magnetic train localization. The main research questions for this experiment were:

- What is the accuracy and availability of a magnetic train localization in urban and high-speed scenarios?
- How good does it work in long tunnels in terms of availability and accuracy?
- Is it possible to identify a track change at a switch inside the tunnel?
- What is the accuracy and availability of the magnetic odometry?
- How do different measurement locations and heights affect the localization?
- Is it possible to use different mounting positions, or different trains for a localization?

- How do generators, power lines, and motors affect the magnetic train localization in terms of electro-magnetic combability (EMC)? Are there unfortunate mounting locations in the train?
- How does a magnetic emergency brake affect the measurements, localization and a possible map?

IV. TRAIN EXPERIMENT

In 2021, we conducted a measurement campaign with the "Advanced TrainLab" from Deutsche Bahn (see Fig.1). This train is a former passenger train for the German high-speed and long-distance service "Intercity Express (ICE)". The train is now a rolling laboratory with two large antenna platforms, racks and contains also sensor data recorders from different projects. The train is a special short train with four cars and a length of 106 m. Each car has an own 560 kW power unit with Diesel engine, generator and electric traction motors. The train can hence access all tracks without the restriction to electrified tracks.

Figure 1: Rolling laboratory: "Advanced TrainLab" from Deutsche Bahn.

The experiment was conducted with a total of 28 magnetic sensors at different positions on the train. Each magnetic sensor measures the magnetic field in three axes (3-D). The magnetic sensors were built in arrays and laid out in special patterns across the train. An 11-element array was placed in various positions in longitudinal, cross and vertical direction for a fine-grid measurement with a spacing of 20 cm. Another array with two times five sensors was placed inside and outside of the train. The outside sensors were mounted on a steel frame at the undercarriage and had the same pattern as the inside sensors at the same place in along and across direction of the train. This setup evaluates inside to outside. The third array comprises five elements with different length along the train in different wagons. The reference measurement setup comprised a geodetic GNSS receiver, IMUs, a wheel-mounted odometer and cameras in both directions for the recording of events and for documentation.

The campaign covered over 2200 km in seven measurement days plus one night shift. The urban measurements were conducted on four days in Berlin, the high-speed and tunnel measurement on the high-speed line between Kassel and Göttingen (city where C.F. Gauss was professor). The train runs on the high-speed line were 44 km long. The line has seven tunnels with 21.4 km of tunnels in total, including the longest tunnel with 10.5 km. The experiments were conducted at night in order to be able to perform track changes to the opposite track and different high and low speeds.

V. EVALUATION METHOD

The measurements were evaluated with the signature similarity method. The following preparation of the data was necessary: The train runs were processed to signatures with 3-D magnetic data (X,Y,Z) over a 1-D location. This 1-D location contains samples with $10\,\mathrm{cm}$ sample distances. In this case, the 1-D location is the distance measured from the wheel odometry from the starting point. The transformation of the magnetic data from time to location samples requires synchronized distance data. The magnetic data is resampled with constant distances of $10\,\mathrm{cm}$ via data interpolation and filtered afterwards. Further, 1-D locations of the GNSS measurements were processed and aligned to the signature. This could be achieved with the time-stamps from magnetic and GNSS data. The GNSS data is required for the evaluations.

The evaluation method has the following steps:

- First, one data set of a train run is selected as the reference signature and another train run is selected as the test signature. The test signature is cut in $50\,\mathrm{m}$ pieces.
- Each $50\,\mathrm{m}$ test signature was evaluated to all locations of the reference signature. The result of the similarity computation of each $50\,\mathrm{m}$ test signature are three similarity values over the locations of the reference signature.
- The maximum of the similarity is identified
- The corresponding GNSS ground-truth positions of the 50m test and of the identified location of the reference are compared: a distance of both GNSS positions is computed.
- A location is evaluated as correct if the distance is smaller than a threshold, and incorrect otherwise.

The reference signature had a sampling spacing of $10\,\mathrm{cm}$ and a length of several kilometer, so several 10000 locations. As similarity metric, the Pearson correlation coefficient was selected. With an efficient programming, this method works multiple times faster than real-time on a standard office laptop with MATLAB. There are no real time problems expected with feasible target hardware. The evaluation was conducted with several reference data sets and different test data sets. In a localization algorithm, the reference signature is extracted from the digital map with track ID and 1-D locations on that track. The test signature is then the most recent measured signature.

VI. FINDINGS

The evaluations of these measurements show interesting findings:

An empirical cumulative distribution functions (CDF) was computed for the accuracy evaluation. The accuracy of the inside mounted sensors on the cabin floor was evaluated with an error of better than $1.8\,\mathrm{m}$ in $95\,\%$ of the evaluations. The accuracy of the outside mounted sensors was evaluated with an error better than $1.5\,\mathrm{m}$ in $95\,\%$ of the evaluations. The ground truth was a GNSS receiver with online corrections.

With a calibration, it is possible to use different sensors in along-track direction for the test and reference signature. Different sensors with different heights and different cross-track positions degrade the correct evaluations.

The magnetic train localization works in tunnels. It is possible to identify the track and a track change at a switch. The tunnel was evaluated with a given accuracy threshold of $20\,\mathrm{m}$. Up to $98\,\%$ of the evaluations were correct of the outside sensors. The outside sensors performed similar with $100\,\mathrm{km/h}$ and below, and with up to $200\,\mathrm{km/h}$. There is no further speed dependency once the magnetic signals have been transformed to the spatial domain and filtered.

The effect of the magnetic track brake of this experiment is analyzed in Lehner et al. (2022). The magnetic brake can change the signature permanently on a small section.

VII. CONCLUSION

The magnetic train localization can be used in long tunnels for the track identification and the along-track localization. The magnetic train localization accuracy in along-track is comparable to GNSS positioning accuracy. Although the comprehensive research questions are not jet fully answered from the large data set. The current work focuses on further evaluations and on real-time algorithms with multiple sensors for localization with enhanced quality evaluation and mapping algorithms.

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