A Precise and Reliable Train Positioning System and its Use for Automation of Train Operation

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***Abstract*—For train positioning purposes, modern train control systems usually use a mix of on-board sensors providing relative measurements (like odometer) and infrastructure equipment (such as balises) for absolute positioning. In order to overcome the disadvantages of fixed installations for positioning along the track, a modular on-board positioning system based on GNSS (Global Navigation Satellite System) is being developed in the German national research project *PiLoNav*. GNSS receivers provide absolute positioning information, whenever satellite signals are available. The measurement accuracy can be augmented using relative positioning with respect to a reference station, e.g. with RTK (Real-Time Kinematic) algorithms. Additional on-board sensors are integrated into a multi-sensor framework and can be used to increase both accuracy and reliability of the position information. Alternative sensor configurations can be examined within this framework in order to identify a solution for a cost-efficient positioning system which delivers values with high accuracy and reliability. The obtained positioning information will be provided to different applications on-board with the aim to increase the level of automation in different train driving tasks.**

***Keywords*—Satellite navigation systems, Rail transportation, Automatic control.**

I. INTRODUCTION

Knowledge about the position of each rail vehicle in the route network is compulsory for both safety and non-safety relevant applications.

Nowadays, the positioning of trains for safety-relevant applications is usually realized by track-side equipment or a combination of track-side and vehicle-borne systems. Whereas in the conventional railway network positioning precision is only at the level of track vacancy detection sections or lower, high precision train positioning is to be found in highly automated rail systems only. Because of the high cost e.g. associated with the required reliability and accuracy of the positioning solution, they are mainly applied on lines with high traffic demand, which justifies the expenses from an infrastructure manager's point of view. Examples are:

TABLE I
CLASSIFICATION OF ACCURACY REQUIREMENTS FOR THE TLU

Measurement value	**Required Accuracy** $v \leq 30$ **km/h**	$v > 30$ **km/h**
Position along the line	0.25 m	1.0 m
Height	1.0 m	1.0 m
Speed	0.1 m/s	0.5 m/s
Acceleration	0.1 m/s^2	0.1 m/s^2

- European Train Control System (ETCS) Level 2: The positioning is based on absolute position information from balises laid along the track and use of odometry on board. Only little information can be found how many balises have to laid for this purpose. In [12], balise position uncertainty and geographic data uncertainty is given with typically 5 m, odometry errors resulting from tachometer errors are given with typically 1 % of the distance from the last balise.
- "Trainguard MT" [10]: The current generation communication based train control (CBTC) system is based on wireless communication between track and train, continuous train positioning and train integrity monitoring. Positioning is based on a solution of fixed point balises and on-board odometry (radar, wheel counter). More balises are laid close to target points along the track in order to improve the positioning accuracy.
- "CRV/ AVV" [1]: This is an automatic train operation system (ATO) in commercial operation in Czech Republic on some heavy-rail lines, e. g. to permit automatic driving according to the principles of energy-optimal train control. Therefore, the lines are equipped with specific balises, wheel-counters are used for relative positioning on the train. The precision for automatic target braking is given with 2 m.
- "LZB" [2]: On some High Speed Lines in Germany and Spain, but also in the Munich S-Bahn system, the system LZB was installed for improved safety and traffic flow. The positioning principle is fundamentally different from the above mentioned systems. Umbilical cable loops are laid along the track, which are used for both safe data communication and positioning. The on-board system detects crossings of the cable (every 100 m) and determines the position between these crossings using odometers.

All above cited systems require the use of fixed installations along the track, whose costs are at the infrastructure manager side only. These trackside installations might require little maintenance effort themselves, but can cause significant additional effort during regular track maintenance. Antennas

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which are to be mounted on the train have to fulfill high requirements on robustness as they are mounted below the vehicle and thus are exhibited to e.g. snow, ice and ballast.

With the operation of Global Navigation Satellite Systems (GNSS) and their further improvements new opportunities arise with respect to the development of more precise systems which provide positioning information on board the vehicles. The goal of pure train based high precision positioning is to reach a higher level of automation on-board of the train for the railway undertaking without investments in the infrastructure. Then the railway undertaking which also benefits from automation can make up an independent business case.

A variety of projects have been conducted with the aim of developing GNSS-based absolute positioning systems e.g., [3], [8]. The major drawback of previous projects and developments is the lack of an integrity indication which is obligatory for safety critical applications. Moreover, several systems do not reliably provide track-selective positioning information, and also precise height information is not always available because of imprecise digital maps or inaccurate positioning systems, although it is especially relevant for energy-saving purposes. Some systems do provide continuous and accurate positioning information, but the interface is restricted to one application only and thus, the positioning information cannot be used easily for other purposes.

The results of the project *PiLoNav* "Precise and Integer Localisation and Navigation in Rail and Inland Water Traffic" are meant to overcome these constraints. The project is funded by the German Federal Ministry of Economics and Technology from 2010 until 2014. The aim of the project is the development of a sensor fusion based positioning system for the highly precise determination of the position, movement and time of a rail vehicle. The integrity of this data has to be determined as well. This information shall be provided centrally on the vehicle. By the means of this system new rail and inland water specific applications are developed and tested. However, in this contribution, the focus is on the rail specific developments. The **T**rain **L**ocation **U**nit, called TLU, is designed for an operation on both heavy and light rail including tramway vehicles. Due to the central role of GNSS in the system, the TLU is not intended to be installed in metros.

The TLU will provide precise information on the train state. This can be used as an input for real-time control applications, e.g. for automation of train control. The precision requirements for the TLU depend on the control applications themselves. Target braking (towards stations or signals) is seen as application of highest precision requirement, controllers need precise position information especially at speeds close to standstill. At higher speeds, even small unknown time delays in the control loop would render a very high position precision useless: if the train moves at 36 km/h and an unknown time delay of 0.1 s exists, the train has already moved 1 m during that time delay. Thus, the precision requirements can be set less stringently for higher speeds.

The requirements as aimed at in the project are summarized in Table I. For the low-speed category the requirements on the accuracy of the position along the line as well as the speed are higher than for speeds above 30 km/h.

This paper presents the overall system concept of the TLU as well as innovative solutions for railway applications based on this system, explains the use cases and highlights potential benefits.

II. SYSTEM CONCEPT

A. Multi-Sensor Framework

The Train Location Unit (TLU) is developed as a modular and flexibly expandable positioning system. The total system is subdivided into subsystems, which are connected to each other via specified interfaces and a central communication hub. Knowing these interfaces, subsystems can be easily replaced or added. Fig. 1 shows the functional system architecture of the TLU, and a sample of sensor and application subsystems which are not part of the TLU.

The core of the TLU are the subsystems of the level 1 and level 2 processing. Therein the various sensor data are combined by applying different fusion algorithms in order to determine the vehicle position. The level 1 processing module works with raw data of the level 1 sensors. These are at least a GNSS antenna and receiver as well as an inertial measurement unit (IMU), which is a common combination also for the positioning of vehicles of other means of transport. The positioning result of the level 1 processing is provided in a PNT-I data set (position, navigation, time and integrity). The position includes both WGS84 (World Geodetic System 1984) coordinates and the direction of travel. The navigation data refer to the motion of the vehicle in terms of speed, acceleration, orientation and angular rates. For each of the measures an integrity value is computed, which states whether the variance is below a predefined threshold.

Rail vehicles always move along a defined track in one dimension only. Therefore sensors for speed or distance measurement along that dimension can be used to improve the measurement accuracy. Further sensors can be integrated, which determine reliably on which of several parallel tracks a train is moving, the so-called track selective positioning. This is realized in the level 2 processing module by combining the PNT-I data of the level 1 processing module with additional level 2 sensor data (e.g. laser scanner and speed sensors) and the description of the route network which is stored in a digital map database. The digital map subsystem does not only provide topological and geometrical but also topographical and operationally relevant geodata. Applying the digital map for map-matching algorithms enables the fulfillment of the track selectivity requirement. The output of the level 2 processing is a dataset called PNT-I+m data which contains in addition to the PNT-I dataset also the ID of the track the train is traveling on and the position along that track.

This dataset is then broadcasted using the fast UDP (User Datagram Protocol) to the different applications which are outside the scope of the TLU. The applications have access to the digital map inside the TLU which guarantees consistent use

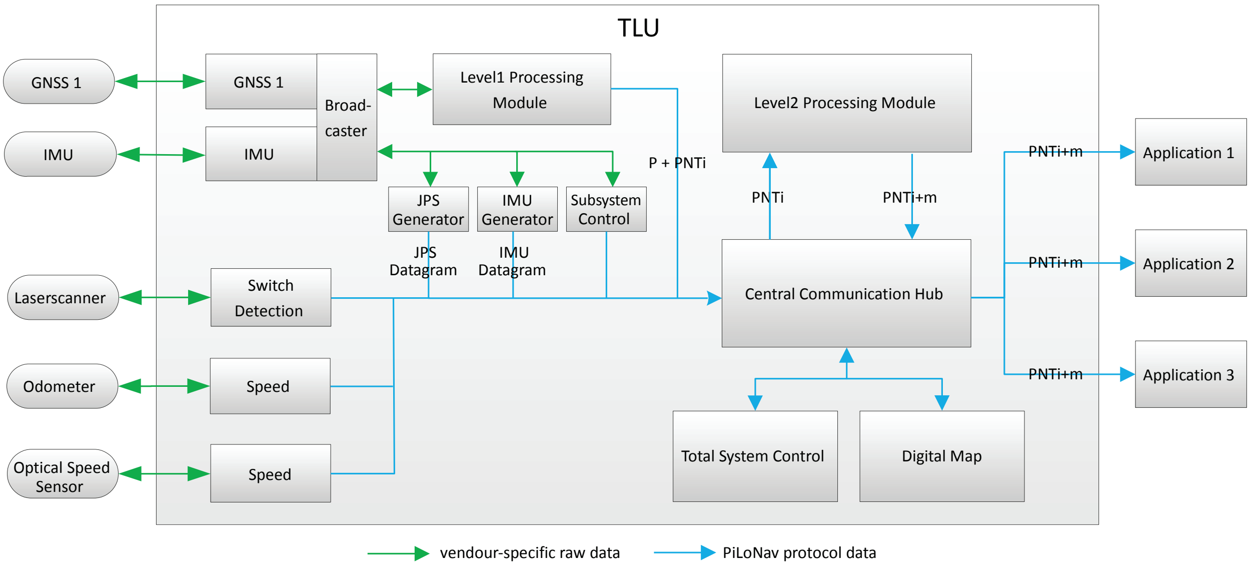


Fig. 1. Overview over the System Architecture of the TLU

of the PNT-I+m coordinate system throughout the positioning and application modules.

Both processing levels are composed of a number of processors, the smallest possible software unit which fulfills one or more functionalities of the demonstrator and cannot be subdivided. Several processors are interconnected to more complex software modules in the form of processor chains. The modular architecture of the TLU, especially of the processing modules, allows an easy adaption of the systems in accordance with the given requirements and existent constraints later on. The central communication hub routes all sent messages on the basis of data telegrams of all types towards the respective target sub systems.

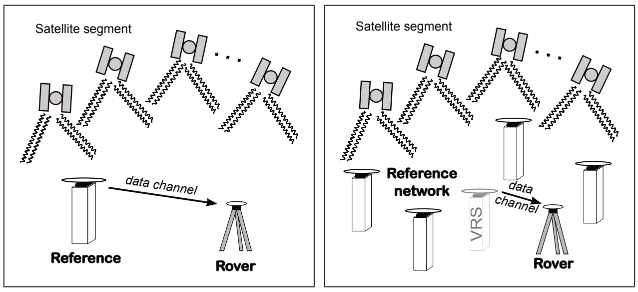
The system control is hierarchically designed and consists of three main components: the total system control, the different subsystem controls and the human machine interface (HMI) of the system control. The total system control serves for the monitoring and control of the subsystems and the system as a whole.

The sensors themselves are not part of the TLU. However, since they are the basis for the TLU the most relevant ones including the digital map and their functions are described in the following paragraph. Some general railway map-matching principles are outlined afterwards.

B. GNSS-RTK

In the last decades Global Navigation Satellite Systems (GNSS) have changed the navigation of vehicles. GNSS is the generic term for different systems, such as GPS (United States), GLONASS (Russia), BeiDou (China) and the future Galileo (Europe).

The achievable accuracy of a navigation system is an important criterion for a lot of applications. With stand-alone GNSS positioning, an accuracy of 10 m can be reached today. Code based Differential GNSS (DGNSS) enhances the horizontal accuracy below one meter under ideal circumstances [6]. The accuracy of the height is worse by a factor of 1.5 to 2 [6]. If cm-level accuracy is needed for real-time applications, only Real-Time Kinematic (RTK) can be considered. For that purpose phase observations on both frequencies are required in addition to pseudorange measurements. The reachable accuracy of all GNSS positioning types depends on many factors, for instance shadowing effects, multipath, or Dilution of Precision (DOP) factors.



(a) The reference station is a single receiver

(b) The reference is a Virtual Reference Station (VRS) with its observation being calculated from a network of reference stations

Fig. 2. Different ways of realizing real-time kinematic (RTK)

RTK further uses the relative positioning approach, which can reduce or eliminate various errors (e. g. orbit, satellite clock, troposphere and ionosphere) by differencing simultaneous measurements of two stations. Due to subtraction of observations only the vector between the two stations can be determined, also known as baseline. If the position of one station (reference) is known, the calculated vector can be appended so that the absolute coordinates of another station (rover) are computable.

The described differentiation is only possible, if the phase observations of the reference station are transferred in real-time to the rover (see fig. 2 a). For that purpose a suitable communication channel must be available. The bandwidth of the data channel is dependent on the number of the visible satellites, e.g. about 3000 bps for 12 satellites. In the field of surveying, mobile internet are used as data channel.

Due to decorrelation of errors between reference and rover stations the length of the baseline should not be longer than 20 km. Otherwise precise positioning is not possible mainly because of the ionospheric effects. These distance dependent errors can be modeled in a network of reference stations. Depending on the implementation either virtual observations (VRS) (see fig. 2 b) or area correction parameters are transferred to the rover. Network RTK services are offered in many countries. SAPOS, ascos, "Trimble VRS Now" and "SmartNet Germany" are existent services in Germany.

On the expansion of railway networks, network RTK services are the most suitable solutions for precise train positioning systems.

C. Other Sensors

The output of GNSS receivers is characterized by a long-term stability of the data but it misses short-term stability. Since data of inertial measurement units (IMU) show converse characteristics they are combined with the GNSS data. IMUs provide information on the accelerations and turn rates in the three dimensions in space.

An optical sensor is used to improve the accuracy longitudinally to the track. It enables a slip-free speed measurement of the vehicle. The slightly structured, moving railhead is illuminated with LEDs (light emitting diodes) and the picture is analyzed by diffraction gratings. The distance results from the integration of the speed values over time.

The information derived from a laser scanner is mainly used to detect switches and the way in which the rail vehicle has passed them. Thus it enables a track-selective positioning and improves the localization transversal to the driving direction. The laserscanner chosen for the TLU emits signals at a wavelength of 905 nm (infrared) with a maximum field of view of 190°.

The laser scanner is also used to detect characteristic elements of the track superstructure and the surroundings, such as signal posts and tunnel portals. Knowing the exact position of these elements from the digital map they can be used as absolute reference points in the positioning algorithm, and in this way, they help to improve the position accuracy also in longitudinal direction.

D. Map-matching approaches

While during normal operation a train always moves along the railway network, the absolute position as determined in level-1 of the TLU (usually specified in WGS84 coordinates also referred to as world coordinates) might not be on that network due to measurement errors as illustrated in Fig. 3. The so-called map-matching is applied which serves for two main purposes:

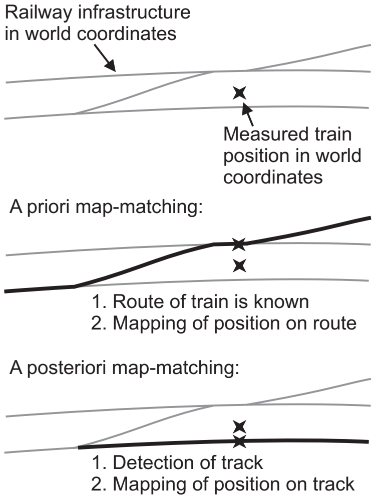


Fig. 3. Comparison of different map-matching approaches. It can be seen that depending on the selection of the track a different position is obtained.

- improve positioning accuracy by reducing the search space to the actual railway network,
- transform the world coordinates delivered by the TLU to coordinates in the railway network which allow for the applications to compute distances to objects along the route of the train.

Two basically different approaches can be chosen for map-matching as illustrated in Fig. 3.

For any safety critical or operational application with high precision requirements on positioning, the knowledge of the future route of the train is essential to have on board of the vehicle, e.g. in large railway stations, there might be many different entry routes with different lengths and permitted speeds. Then, a priori map-matching can be executed, i.e. the multi-dimensional world coordinates can be transformed into a single coordinate "position along the route" using the route knowledge and a model of the network. The route of the train is known in advance e.g. in state-of-the-art Communication-Based Train Control systems (CBTC) [7].

The more general map-matching case and also the one which is more widely examined in the literature [8] is the case where the on-board systems have no knowledge which route a vehicle will take. The first step in this approach is the identification of the track the train travels on. This can be done e.g. using a sequence of positions describing the movement of the train in high resolution and matching the recorded line to the map or by detecting the direction a switch has been passed using particular sensors. In a second step, the position along that track is determined e.g. using point to line matching. As the track is only identified after the train already travels on it, this approach could be called reactive or a posteriori. It is useful e.g. to detect on which platform a train will arrive inside bigger stations and then to conclude on which side the doors will have to open (for passenger information systems or automation of door release).

Both map-matching applications require the use of a digital map, where a translation between world coordinates (here: WGS84) and rail coordinates (usually track ID and position along the track) is described. The digital map used in the project *PiLoNav* contains the topology of the railway network, its geometry and further application specific information. Therefore the map is structured into layers. Based on the topology layer with the node-edge model of the route network and the geometry layer with the coordinates of all relevant infrastructure elements it can easily be expanded by additional layers. The digital map is stored in a database, data can be imported or exported in railML® standard version 2.2 [11]. A project specific extension was made to railML® to describe the accuracy of the map.

III. APPLICATIONS

A. Safety layer

On the safety layer it will be shown in how far the precision and reliability of the speed and position of the proposed *PiLoNav* positioning system can be used within safety relevant ATP (Automatic Train Protection) applications. Modern ATP systems like ETCS or CBTC are able to consider positioning precision in the computation of the braking curve. Thereby they are based on the assumption of a positioning error which is growing linearly over distance. This assumption is based on the application of wheel counters (odometers) and the tolerated limits of the wheel diameters. The error is reset at reception of fixed-position balise telegrams to the position error of the balise itself.

In the *PiLoNav* system, the current estimated measurement error is given, but in contrast to the linear prediction made for conventional systems, no reliable worst case prediction for the positioning error can be made for the overall positioning solution. For the safety layer it shall therefore be assumed that the maximum error is still to be determined by the linear odometry error. If the actual positioning error is smaller than the currently estimated positioning error, the maximum train position can be reset to the estimated train position plus the measurement error as computed by the TLU.

B. Operational layer

The operational layer contains ATO functions, in particular functions for energy-optimal speed control and time-optimal target braking are implemented. The literature on ATO and energy-optimal train control is scarce, one implementation by Siemens is described in [4]. It is explained that the simulated speed curve is taken as input for acceleration control. In case of deviations from the simulated coasting trajectory, regulative actions are taken. In metro systems, where that described controller is in operation, these deviations might be small, but in heavy rail systems targeted here wind and other weather conditions might lead to e.g. varying coasting behaviour more frequently. Furthermore, small control values (either tractive effort or (electric) braking effort) usually have a low efficiency and should therefore be avoided [5]. In our approach this negative effect is avoided by applying coasting directly (setting tractive and braking effort to zero) and by re-computing the optimal trajectory in case of deviations.

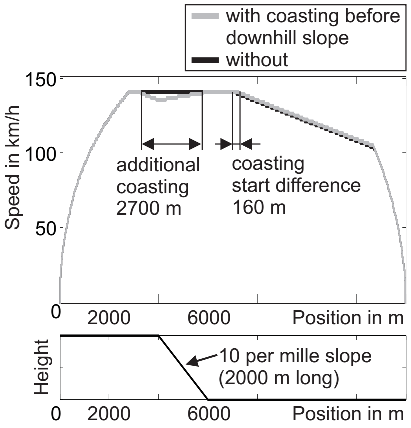


Fig. 4. Example for a trajectory using coasting before a slope compared to a trajectory not using coasting before slopes because of position and speed inaccuracy. The differences in the coasting phases lead to energy savings of 4 % of the solution with coasting before the slope. It should be noted that the length of the final coasting phase is only minimally different.

Using high precision position and speed information for real-time automatic train speed control could open more potentials for energy saving also compared to Driver Advisory Systems as they are now in operation on several railways in Europe [9]. These are mainly based on GPS. Due to its low precision in speed and position, these systems cannot reliably determine whether coasting phases close to maximal speed, e.g. before downhill slopes shall be advised, because it cannot reliably be determined how the driven speed relates to the permitted (and supervised) maximum speed. Fig. 4 gives an example for such a situation, where the principles of energy-optimal train control suggest that the train should start coasting shortly before a downhill slope of 10 ‰ in order to reduce its speed from line speed to 5 km/h below line speed at the beginning of the slope and return to maximal speed transforming potential energy to kinetic energy on the downhill slope. With inaccurate and unreliable positioning technology, advising this coasting regime is critical because advising too early might lead to a decrease in speed which cannot be recompensed by the slope and the driver might then question the given advise, which might lead to a general bad acceptance of the advisory system.

The problems mentioned can be solved with the approach described here. The high availability and precision of the *PiLoNav* positioning solution allow to use the energy-optimal trajectory which can save between 1 and 8 % of energy (4% in the example given in Fig. 4) compared to the trajectory which only coasts before target braking and which is therefore not energy-optimal. The amount of energy saving depends of course on the exact track geometry (size and length of slope) as well as vehicle running resistance, but generally it can be stated that the solution with coasting before slopes is always better than a solution not using this policy.

The high precision of the positioning solution is a prerequisite for automatic implementation of the energy-optimal trajectories in an ATO like system. Because of the mentioned advantages it might even be interesting to replace GPS as sensor in Driver Advisory Systems and thereby increase their applicability to tracks with bad satellite reception conditions.

C. Modeling layer

The main task of the modeling layer is to detect differences between the actual acceleration/ braking behaviour and the assumed model for both as known in the on-board systems and used e.g. on the operational layer. Such differences could be caused e.g. by wear and tear, by bad friction between wheel and rail or (in manual train driving) by driver behaviour. The most frequent and severe of these points are bad weather conditions, e.g. during the leaf fall season. This phenomenon occurs on locally restricted areas (high air humidity, trees in the area), but might have significant impact on the overall timetable adherence of all trains in the systems (trains need more time for braking/ accelerating than normally). Our goal is to identify such a situation automatically and – by using this knowledge in the control of the entire fleet – prevent delays and avoid stops being missed or signals being passed at danger due to bad braking conditions. The subject is of particular relevance for frequently stopping (passenger) trains with usually high braking/ acceleration effort and comparatively low mass (e.g. EMU/ DMU).

Therefore the actual braking/ tractive effort shall be computed from the measured acceleration of the train as provided by the TLU subtracting the resistive forces (running resistance, track resistance) from it. It should be noted that train mass and its distribution along the train have an influence on this equation and should be known as good as possible.

If the obtained actual braking/ tractive effort is substantially smaller than the available maximal effort, it will be checked whether this deviation is specific for the train (or for the train/ driver combination in manual driving mode) or the track by comparing the values obtained for different consecutive braking/ acceleration regimes of the single train or by comparing it with other trains.

D. Helper function layer

Further functions which can be automated with high precision positioning are

- operation of the traction circuit breaker at borders of power supply areas (as mentioned e.g. also in the ETCS specification),
- application of wheel flange lubrication in curves in order to reduce noise,
- door release at platforms

which are all regarded under the helper function layer. The task on this layer consists of identifying a starting point where to take a certain action and a termination point where to stop afterwards. For door operation, further the side of the train where to open the doors needs to be decided. This requires the identification of the exact track and the availability of platform information in the track database.

IV. CONCLUSION

Train-based absolute positioning with high accuracy and reliability is one means to increase automation of train operation. As no installations on the track are necessary, the railway undertakings can create a business case and project plan independent of costly and time-consuming track work. A data interface between traffic control and on-board positioning module should be available for the optimal use of the high accuracy positioning technology.

The developed positioning framework will be demonstrated on a real-world railway in Saxony from autumn 2013. It shall be examined, whether and how different sensor setups and algorithms can fulfill the accuracy requirements under difficult satellite signal reception conditions (tunnels, narrow valleys). Some of the described applications will also be tested in the real-world railway, however those of the safety layer will be tested in a simulator environment only.

Other possible applications using the high-precision positioning information shall be examined in the near future. These are e.g. automatic coupling of trains or the control of tilting trains.

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