GNSS-BASED SENSOR FUSION FOR SAFETY-CRITICAL
APPLICATIONS IN RAIL TRAFFIC

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ABSTRACT

Due to the availability of precise satellite navigation systems, namely GPS and in the near future Galileo, which provide reference position, time and integrity information on a global and uniform basis, rail traffic is facing a revolution in terms of flexibility of operations. Autonomous satellite navigation receivers combined with a communication subsystem, so-called telematics systems, are used in a vast variety of ground transport applications today, predominantly road and maritime transportation. The railway sector was more reluctant in the past, but becomes more and more convinced about the benefits of the GNSS-based telematics technology.

To conquer these demands, a mobile telematics prototype system called INTEGRAIL has been developed by Kayser-Threde and Bombardier Transportation during the last three years. The basic objective of the INTEGRAIL development was to demonstrate the profitable use of GNSS for advanced rail traffic management. INTEGRAIL is the first step towards providing train position, velocity and heading by means of satellite navigation to safety-critical rail applications. At this stage it allows already for the more profitable exploitation of low-density rail lines. Eventually, INTEGRAIL will provide a GNSS-based odometry interface within the already emerging ERTMS standard to serve high-speed lines as well.

The working principle of INTEGRAIL combines satellite position data with traditional train sensor readings such as odometry. The INTEGRAIL platform consists of a set of state-of-the-art commercial components, which are integrated into a transportable 19” box (‘mobile unit’) and installed on-board the locomotive. A dedicated sensor fusion software performs cross-checks with a digital route data base on a regular basis and provides integrity-checked position, speed and heading data. INTEGRAIL also caters for communication with a dedicated control centre for remote monitoring and configuration control. The communication scheme is based on GSM and allows to remotely monitor the performance and to control the configuration of the mobile unit operating on the train. Extension to GSM-R is planned.

’In-the-field’ tests in Austria and Belgium allowed to assess the system’s performance in terms of accuracy, integrity and availability in operational day-to-day scenarios, and hence to prove the feasibility of GNSS-based sensor fusion for future use in safety-critical train location, train control or transportation of dangerous goods. The paper reports about the development, testing, performance and individual benefits of the INTEGRAIL system. Main focus is on the results of the field tests and the assessment of the system’s performance. An outlook to compatibility and interoperability with the applicable European rail standards like ERTMS/ETCS is given.

1 INTRODUCTION

Autonomous telematics systems, i.e. location sensors – preferably GNSS receivers and/or odometers – combined with a terrestrial data communication system – mostly GSM – are used in a variety of land transport applications today, predominantly road and maritime. In the railway sector, which has been somewhat reluctant in the past, more and more requests are raised to make profit of the telematics technology, too. In this area, usually non-safety and safety-critical applications are distinguished. Safety-critical applications which include train control and signalling, passenger traffic or transportation of dangerous goods, show very demanding requirements in terms of availability, continuity and integrity. In order to fulfill these high performance demands complementary positioning sensors (e.g. accelerometers, digital track maps) and alternative communication components (e.g. GSM-R, UMTS, satcom) have to be grouped around the receiver/communication core. In addition, compatibility to the new European rail traffic management and train control standard ERTMS/ETCS is mandatory.
Since mid of the 1990’s, both Kayser-Threde (KT) and Bombardier Transportation (BT) have been successful in the area of non-safety critical wagon tracking and fleet management applications with their systems Railtrac-KT [1], TEMA (Traktions-Energie-Management) [2] and INTERFLO 50 [3]. Since ca. the year 2000, strong efforts have been undertaken in order to solve the higher demanding navigation tasks in safety-critical railway applications like train control and train supervision. In this area a GNSS receiver usually serves as a basic sensor which is enhanced by other navigation sensors and by an integrated fault tolerant sensor fusion software. The INTEGRAIL system [4], [5] is a prominent example for such sensor fusion concept and will be discussed hereafter in detail.

2 INTEGRAIL SYSTEM DESCRIPTION

In high-end railway telematics applications, the primary motivation for selecting a certain sensor combination is – apart from the application’s individual objectives – the complementary characteristics and thus the complementary error behaviour of the sensors. Alongside the track-mounted balise, a GNSS receiver is the only sensor providing absolute positioning information of the moving vehicle. Therefore, this sensor should be obligatory for all combination options. Since relying on an external RF signal, a GNSS receiver is at the same time the only sensor which is not autonomous. This fact essentially is the motivation for combining it with other sensors. To increase the reliability of the GNSS data, the integrity information of a wide-area differential system (EGNOS = European Geostationary Navigation Overlay System in Europe, WAAS = Wide-Area Augmentation System in the U.S.) can be used.

Inertial sensors like gyros and accelerometers provide very reliable information about rotation and acceleration rates and – after integration – about relative velocity and position over a certain period of time (i.e. a few minutes depending on sensor type and quality) with a high frequency (> 100 Hz). These data ideally complement the long-term stable, low-rate GNSS measurements. Moreover, inertial sensors are suitable to bridge bad GNSS signal reception conditions for a couple of minutes and guarantee a constant accuracy of the hybrid positioning solution. In terms of absolute reference, a digital track map promises the highest merits, since an algorithm combining GNSS, inertial measurements and/or track (section) identification will allow robust plausibility checks and finally provide a very reliable and integer position solution. The actual system implementation onboard the train will be very different depending on what train application is being served, but no matter what concept is implemented, it will accommodate a GNSS-based module with multi-sensors. As a typical example, Figure 1 details the configuration chosen for the INTEGRAIL system. The sensor configuration of any other train-borne positioning concept will be very similar.

![Figure 1: Basic block diagram and sensor configuration of the onboard train location system INTEGRAIL.](image)

The most important features of the INTEGRAIL system (ref. Figure 2) are:

- permanent, hybrid, fault tolerant position determination via GPS/EGNOS receiver (CMC Allstar 12-channel L1), odometer, along-track acceleration sensor (Crossbow CXL02LF1), fibre optical sensor for measuring the vertical rotation axis (i.e. the azimuth or heading angle, KVH E-Core 1100 or 2030) and digital route map;
- specification of the hybrid positioning solution accuracy: ±10 m along-track; ±1 m cross-track (2σ) for safe discrimination of parallel tracks;
• specification of non-availability: test system < $10^{-4}$, GNSS positioning solution < $10^{-5}$ per 2 km or 20 s of the travelled distance;
• application possible in safety-critical rail traffic according to definition of the new European standards (European Train Control System, ETCS) via compatible H/W and S/W interfaces.

Figure 2: INTEGRAIL system mounted in driver's cabin. Laptop is used for test data download only.

Up to now, four INTEGRAIL mobile units with slightly varying features and characteristics have been procured in order to assess the optimum configuration for the intended purposes.

3 INTEGRAIL SYSTEM VERIFICATION

The INTEGRAIL mobile units followed a dedicated static and dynamic test program. For the CMC Allstar receiver, static tests with different set-ups were conducted (with/without EGNOS, various masking, shadowing). The results approved that the quality of the ionospheric data provided through EGNOS is comparable to direct measurements, however, the scatter of the EGNOS data was slightly higher due to the regular message updates which introduce jumps in the corrections. The overall static performance was very good with residual horizontal position accuracies in the 2 to 3 m range (3 to 5 m in height, in the corrections. The results

Field demonstration tests have been run with the four individual units from March to December 2003 on dedicated tracks in Austria (LogServ, Linz) and in Belgium (SNCB) and successfully accomplished. To have an independent reference, DGPS dual-frequency carrier measurements have been executed on the driven tracks. Data from close-by GPS reference stations were used to evaluate the logged raw data. For generating the position residuals, the integrated solutions were compared to the GNSS-only solutions which were corrected by the recorded reference station data. Each INTEGRAIL mobile unit was shown to be able to provide reliable, high-rate, integrity-checked train position, velocity, time (PVT) and heading data on a continuous basis. The units can determine permanently and under most environmental conditions the train’s current position (accuracy ca. 5 m, 1σ), velocity (1 km/h, 1σ), quality indicator (confidence level close to 100%), direction of movement and health status of the mobile unit and its components.

3.1 GNSS Sensor Verification

In particular the behaviour patterns of the implemented GNSS sensors were investigated during the field tests. Figure 3 shows samples of the GNSS positioning results (GPS+EGNOS) in the Linz, Austria, area. The reference data applied were calibrated by carrier DGPS with an accuracy of about 10 cm. It was noticed that close to buildings increased multipath and, thus, positioning errors as shown in the figure were likely to happen. Multipath was amplified when nearby buildings had large metal surface areas. This was found to cause positioning errors sometimes larger than 100 m. The figure details two examples where metal-surfaced buildings (e.g. furnaces) and poor satellite visibility caused large GNSS positioning errors.
With the digital track data base that was available, the recognition of single tracks could in general be established, the accuracy, however, was not sufficient for safe track detection requiring over 99% confidence under the conditions shown. Incomplete track data bases as well as multipath and shadowing influences were found to be the two major limiting factors of current GNSS positioning. Under the present constellation and software, multipath and shadowing are cause for greater positioning degradation concern than any potential malfunction of the GNSS signals.

### 3.2 System Accuracy Verification

The accuracy of the INTEGRAIL hybrid position solution has been verified using the DGPS reference solution. For the Austrian tests, the reference data have been acquired with a Novatel Millenium two-frequency receiver and the IGS station Linz. The residuals of the INTEGRAIL hybrid data with respect to those DGPS reference data are shown in Figure 4, with outliers due to multipath (residuum > 50 m) removed.

![Figure 4: INTEGRAIL horizontal positioning accuracy (histogram of the horizontal position residuals).](image)
As can be derived from the figure, the mean accuracy of the INTEGRAIL hybrid solutions w.r.t. the DGPS reference was around 3.6 m with a standard deviation of about 5.4 m, whereas the median (excluding track selection errors due to missing track segments/switches in the digital route data base) was as low as 0.79 m. This is an exceptional good performance result and supports the selected combination of sensors and the underlying hybridisation algorithm. Two side peaks are visible at approximately 7 m and 14 m which can be understood as false identification of parallel tracks. They are raised by missing tracks in the track catalogue, since both the reference data base and the track data base generation processes have not covered all tracks and switch points in the operation area.

3.3 System Remote Monitoring

For monitoring and commanding of the mobile units, a central control facility was set up at Kayser-Threde’s premises for transmission and reception of the SMS messages (Figure 5). The facility allows a multi-user access to the message and command database via a TCP/IP-based internet browser.

![Figure 5: GUI of KT’s central facility for remote monitoring and commanding of mobile units (detail).](image)

The location and status data of the individual mobile units running on the trains can be accessed through the GSM link in combination with digital maps. The configuration for communication and recording can be changed individually (password protection) any time via Internet (TCP/IP) directly at the train operator’s desktop.

4 STATUS AND PERSPECTIVES OF GNSS-BASED TRAIN CONTROL IN EUROPE

Train operation requires safe separation of trains while travelling on the same track, and safe separation at switches. Any failure of the positioning system must result in a safe situation, usually with trains being brought to a stop. Information, e.g. about the clearance of the track, the status of the points and switches, the location of the trains, is collected in a control centre. It must be continuously updated with the location, speed, identity and direction of each train in its area. The control centre then computes which movements are safe for each train against its timetable, sets a safe route by interlocking points and issues moving/stop signals to drivers.

The train position determination function in the existing systems is normally achieved by means of track circuits and/or axle counters which check if a rail route is free or occupied by other vehicles. The national railway administrations of the EU have historically developed their own different and incompatible signalling as well as train positioning systems. Presently, about 15 different systems are in operations across the EU (without accession countries). This has made operating trains between different countries and lines difficult since locomotives have to be changed at the border or the locomotives have to carry equipment for different signalling systems, thereby increasing complexity and cost. In addition, track-side based signalling systems require a significant amount of equipment and are, therefore, expensive.
The tendency towards liberalisation in the transport world means that in future the railways are going to have to compete even more intensively with other modes of transport. To cope with those challenges, the European Train Control System (ETCS) in the frame of the European Rail Traffic Management System (ERTMS) has been specified. It is the future radio-based signalling system for Europe and will not only improve operating efficiency, but also seize every opportunity to reduce acquisition and maintenance costs. The figure below shows the network of high-speed rail tracks in the EU. They will cover ca. 75,000 km in total by 2010 (without accession countries).

Figure 6: Trans-European high-speed railway network incl. planned extensions until 2010.

ERTMS/ETCS has started the evolution that the signalling as well as the train positioning functions are being removed from track to train-side. However, the key positioning component of ERTMS/ETCS – the balise – must still be installed along the track at ca. 1 km steps. GNSS-based train positioning needs no trackside equipment and is significantly cheaper. The ERTMS Users Group has issued a proposal for a common approach towards introduction of GNSS in ERTMS/ETCS [6] and expects that GNSS-based position determination can constitute an attractive complement or even replacement of some existing technologies. The emergence of reliable GNSS services, initially with EGNOS and later with Galileo, is expected to influence the practical implementation of ERTMS/ETCS significantly.

4.1 GNSS with EGNOS

The stand-alone performance of the GNSS Signal In Space (SIS) in terms of accuracy and integrity is not sufficient for many rail applications. It can, however, be significantly enhanced by a wide area augmentation system like EGNOS. EGNOS will be fully operational in early 2005. It implements a warning of system malfunction for the spacecraft (integrity function) and improves accuracy by means of differential corrections (ionosphere, satellite clocks and ephemeris). The EGNOS full service will cover all EU states. The EGNOS performance under normal receiving conditions (no shadowing, 10° elevation mask) is shown in Table 1. The horizontal accuracy stated in the table must be interpreted as requirement tailored to the aviation domain. For rail applications, the achievable horizontal accuracy will always be better than the vertical accuracy due to the better horizontal geometry of the satellite constellation; the achievable horizontal accuracy will be less than ca. 4 m.

It must, however, be noted that the GNSS SIS performance is not equal to the GNSS positioning performance. The GNSS positioning accuracy is also dependent on the geometry of available satellites at user side. The geometry of the tracked satellites can affect the GNSS positioning accuracy. The geometry of the tracked satellites depends not only on the GNSS satellite constellation but also on the environmental conditions. The availability of satellite signals as well as
the geometry of available satellites can be affected by obstacles (e.g. hills, buildings, tunnels). Since the GNSS positioning performance also depends on the environmental conditions and the required performance level, positioning availability can not always be achieved due to unavoidable shadowing of GNSS signals under typical train operation environment. Therefore, GNSS location shall not be used as sole means in a train control system. The hybridisation with aiding sensors is mandatory and a terrestrial augmentation of EGNOS may be needed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal accuracy</td>
<td>16 m</td>
</tr>
<tr>
<td>Vertical accuracy</td>
<td>7.7m to 4.0m</td>
</tr>
<tr>
<td>Integrity risk</td>
<td>2*10^-7 in any 150s</td>
</tr>
<tr>
<td>Time To Alarm</td>
<td>6s</td>
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<td>HAL</td>
<td>40m</td>
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<tr>
<td>VAL</td>
<td>20m to 10m</td>
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<tr>
<td>Continuity</td>
<td>8*10^-7 in any 150s</td>
</tr>
<tr>
<td>Local Availability</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 1: EGNOS performance according to [7].

The approved positioning accuracy of the INTEGRAL prototype system is between 0.8 m and 1.3 m (1σ) if no serious multipath and shadowing influences exist. Taking such effects as multipath influence and incomplete track catalogue into account, the mean accuracy decreases to about 1.8 m (1σ) which, however, is still within the required performance specification of many applications. In terms of integrity and continuity, the present prototype is not yet able to meet the very high performance requirements of train control mainly due to the incomplete track data base. The concept of sensor fusion allows to deselect and bridge bad GNSS positioning, but continuous location data output is only possible with a complete and up-to-date digital track catalogue against which the sensor fusion solution can be reliably cross-checked. A common agreed approach on track data base implementation and maintenance is highly desirable.

### 4.2 Benefits of GNSS-Based Train Location Systems

A GNSS-based train control system will be superior to other train control systems due to its

- lower cost;
- better interoperability (no need of infrastructure equipment);
- performance improvement w.r.t. the existing odometry.

Low cost will be the main driver for implementation of a GNSS-based train control system. For regional and secondary lines, the low density of traffic as well as low business income may accept no expensive signalling investment. The traditional track circuit signalling systems and also the balise-based ETCS signalling system are too expensive for such lines. A GNSS-based train positioning system is expected to be significantly cheaper and, therefore, more effective.

Better interoperability will be another main driver for using GNSS-based train location. As described in [8], ETCS and the existing signalling systems should be equipped in parallel where possible. A long transient phase in which different lines with different systems would exist is most likely. The railways are currently facing an economical and technical barrier to this interoperability problem. Since a GNSS-based train positioning system needs no track-side infrastructure, it can provide a smooth interoperability period without the need for new investments in infrastructure. It operates irrespective of what track-side system is already in place. It will therefore be easier to use a GNSS-based positioning system to overcome the economical and technical barriers of this transient phase (note: not easy but easier; there are still other interoperability problems to be solved, e.g. communication with control centre and interface to interlocking).

A GNSS-based location system will provide not only benefits on costs but also on performance. GNSS can improve the ETCS location performance. The current ETCS onboard system uses odometers as main speed/distance sensors. The error caused by slip and slide of wheels is a major problem which affects odometry performance as well as the safety margin. Resetting this error is only possible when passing spot transmission positions like balises. GNSS can give much
more frequent location references to reset this error. Additionally, as shown by the INTEGRAIL prototype system test results, GNSS-aided contactless location has no wheel slip/slide problem. The accuracy achieved by INTEGRAIL over 60 km route is better than 2% of distance travelled. Therefore, GNSS-aided contactless location will help to solve the wheel slip/slide problem and to improve odometry performance significantly.

5 SUMMARY AND CONCLUSION

In view of trans-European rail traffic, a GNSS-based train control system will be more appropriate for the railway operator than any other train control system due to its lower cost and better interoperability. GNSS using EGNOS will be the first step of introducing satellite positioning into European rail safety applications. In order to serve this field of applications, Kayser-Threde co-operates with Bombardier Transportation (Signal) Germany and other partner companies to realise satellite-based telematics systems which meet the requirements of high-precision applications and highly valuable or safety-critical transports. For that purpose a basic GNSS sensor must be grouped with further position determination sensors like odometer, inertial measurement unit or digital route map. The single data are fused by an integrated and fault tolerant ("hybrid") software.

The high ETCS integrity requirement of train location should be no barrier. The dominant integrity risk of positioning accuracy arises not directly from the GNSS SIS, but through the multipath and shadowing influences. The probability of this kind of risk is greater than that of GNSS SIS malfunction. The high integrity requirements will be ensured by a hybridised GNSS positioning system. Malfunctions will be quickly detected by cross-check of sensors and by assessment against the digital route data base. Based on the same reason, the time-to-alarm (TTA) of 6 s as specified by EGNOS will not be the problem for using GNSS in train control applications (TTA of 1 s is required in critical areas). The only major problem may be the lack of a service guarantee of GNSS which currently relies solely on GPS. The advent of Galileo will significantly improve this situation.

According to the results of the INTEGRAIL prototype system test campaigns, the accuracy of GNSS positioning with EGNOS will be satisfactory for train control applications at low traffic density lines. If some operational arrangements can be accepted by the railway operators, the use of GNSS-based systems can be extended to other lines.

ACKNOWLEDGEMENTS

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REFERENCES