

The high integrity GNSS/ INS based train position locator

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Abstract

Integration of a GNSS receiver with additional inertial sensors can significantly improve the performance and reliability of the train position locator (TPL). However, if the TPL is intended for safety related applications like signalling and train control, it should also be robust to sensor and system failures. This means that the locator must meet the high safety integrity design and have its own diagnostics capable of providing timely warnings to a user in the case of a failure.

This paper deals with the high integrity architecture of the TPL. The architecture consists of the two fundamental subsystems: 1) the dual navigation system providing the state vector estimate by means of the two independent navigation loops and 2) autonomous safety integrity monitor (AIM) which continuously checks the safety integrity status of the locator.

The state vector estimator is based on the indirect robust Kalman filter which continuously corrects the gyro-odometry positioning subsystem by means of the GNSS receiver. The employed microwave Doppler speedometer and the accelerometer provide necessary redundancy for the sensor data validation and integrity monitoring.

The design of the AIM results from the already specified user safety requirements. The basic principle and states of the AIM are described in terms of the position error, protection level and horizontal alert limit. The failure recognition methodology by means of the hypotheses testing is outlined. The performance of the AIM is measured by means of the probabilities of missed detection and false alarm and other parameters.

Keywords: GNSS, GPS, Galileo, INS, railway signalling, safety integrity monitoring, train position determination, protection level, alert limit.



1 Introduction

A GNSS receiver together with additional on-board sensors such as odometer, accelerometer, gyroscope, microwave Doppler speedometer, etc. can significantly improve reliability of the TPL, including train position determination on track sections with limited GNSS Signal-In-Space (SIS) availability. Although reliability of the locator is highly desirable, it does not provide a guarantee of the system performance in case of a fault. If the locator is intended for railway safety related applications, such as signalling or protection of track workers, it is necessary to design the system with **high safety integrity**, i.e. the locator must be robust to a failure.

2 Safety integrity requirements

The user requirements regarding safety integrity of TPL (see table 1) have been already specified within the GNSS Rail Advisory Forum [1]. In table 2 there are defined selected parameters of the Galileo SAS (Safety of Life Services) intended for safety related applications in transport sector including railways.

Table 1: The user safety requirements of the GNSS/ INS based TPL [1].

Kind of Line	Train Position Locator			
	Horizontal	Safety Integrity		
	Accuracy	Alert	Time-To-	Continuity of
	[m]	Limit [m]	Alarm [s]	Service [%]
Corridor/ Station	1	2.5	< 1	99.98
Non-Corridor	10	20	< 1	99.98
Regional	25	50	< 1	99.98

Table 2: Definition of the Galileo Safety of Life Services [2].

Service	Galileo Safety of Life Services Definition			
	Horizontal	Integrity		
	Accuracy	Alert	Time-To-	Integrity
	[m]	Limit [m]	Alarm [s]	Risk [rate/ time]
SAS (Safety of Life)	< 4	11	< 6	3.5e10-7/ 150s 2e10-7/ hour
SAS-L (Local)	< 1	3	< 1.0	2e10-9/ 150 s

As it is evident from tables 1 and 2, safety integrity is described by means of these parameters: 1) **Alert Limit (AL)**, which is maximum allowed position error before the alert has been raised, 2) **Time-to-Alarm (TTA)**, which is the



maximum allowed time between the appearance of the alarm condition and the alarm generated in the output of the system, and 3) **Integrity Risk Rate (IRR)**, which is an appearance of one undetected failure per a given time interval. The *IRR* can be transformed by means of the Kolmogorov theorem to the probability of missed detection P_{MD} , which is the probability of one undetected failure.

Integrity risk (P_{MD}) appears when the position error estimated by the TPL is out of the tolerance region (i.e. *AL* is exceeded) but the integrity monitor doesn't generate the alarm *Don't Use*. In railway safety related applications the integrity risk is usually described by Tolerable Hazard Rate (*THR*), which is derived from the risk analysis of the specific application. However, if the TPL based on GNSS/INS should replace track balise positioning in ETCS, it should meet SIL 4 requirement, which is the highest safety integrity level. Nevertheless, it is expected, that the GNSS/INS based TPL will be introduced to signalling applications with less demanding safety integrity requirements first (e.g. on regional lines) and later on, when this advanced technology will be verified, it will migrate to main corridor lines.

3 The high integrity architecture of TPL

The safety integrity monitoring on GPS satellite system level is currently by the EGNOS Ground Integrity Channel (GIC). The SIS integrity monitoring can be also performed locally by Receiver Autonomous Integrity Monitoring (RAIM). However, both GIC and RAIM can fail due to local effects such as SIS multipath, electromagnetic interference and also insufficient mutual GNSS satellite/ receiver position (high HDOP value) etc.

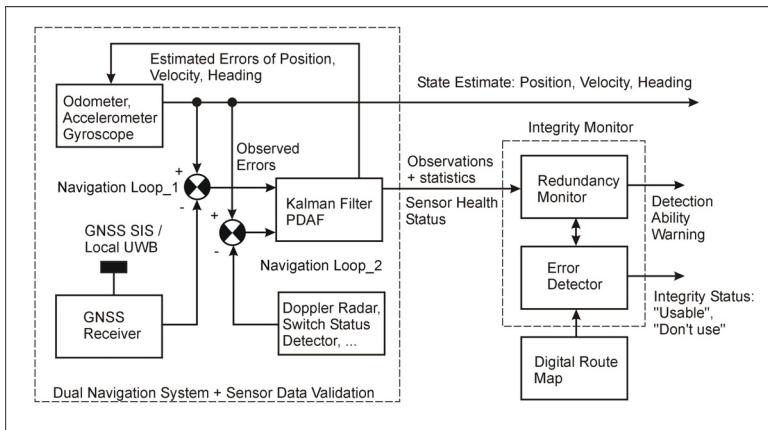


Figure 1: High integrity architecture of train position locator.

Therefore, it is necessary to employ additional sensors (odometer, gyroscope, microwave Doppler speedometer, accelerometer, etc.) and implement so called **autonomous safety integrity monitor (AIM)** on TPL level. Important

role in the AIM has a two dimensional digital map of tracks and switches.

The high-integrity architecture of the TPL is proposed in fig. 1. It is a loosely coupled position determination system GNSS/ INS based with direct feedback and the two independent navigation loops. The main purpose of this setup is to provide sufficient sensor data redundancy. In case a failure occurs, these two navigation loops provide different results. In order to improve the integrity, it is desirable to implement additional independent failure detection tools in each of the loops. It minimises the probability that the error/ failure will remain undetected in this single loop.

The safety integrity monitor (see fig. 1) is actually a diagnosis based on redundant measurements, which continuously monitors states of the TPL. In case of a failure, according to the definition of integrity, it provides timely warning to a user (*Usable, Don't Use, Not Monitored*). The AIM makes decision based on these user requirements: *TTA, IRR, AL* and continuity of service (see table 1).

4 Sensor data validation and failure sources

As it has been recently experimentally demonstrated [3,4], sensor data can be efficiently validated by PDAF (Probability Data Association Filtering) method [5]. As shown in fig. 2, the sensor data validation is based on evaluation of the innovations. The advantage of the method is that the inconsistent or corrupted sensor data, e.g. due to wheel slip, is automatically excluded by the conditional weighting from the data fusion process. The PDAF method seems much more robust for TPL needs than plain Kalman filter (KF). However, in the PDAF method, similarly as in a KF, the potential non-white noise in the validated sensor data can introduce an error in the state estimate, disrupt the sensor data validation process and finally cause a system error, which can be interpreted as a bias. Therefore a diagnosis, i.e. the AIM, should be implemented within the TPL in order to continuously check the potential biases.

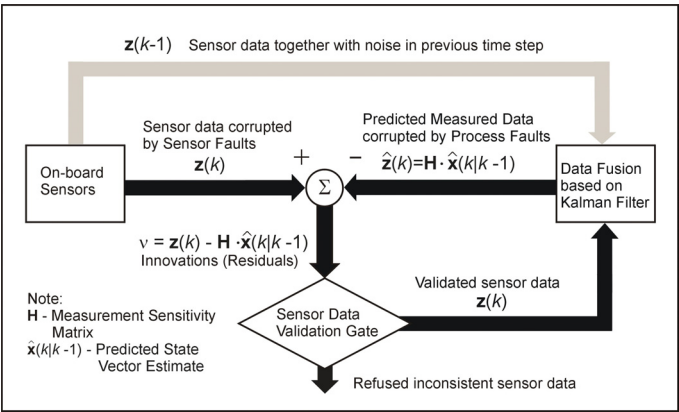


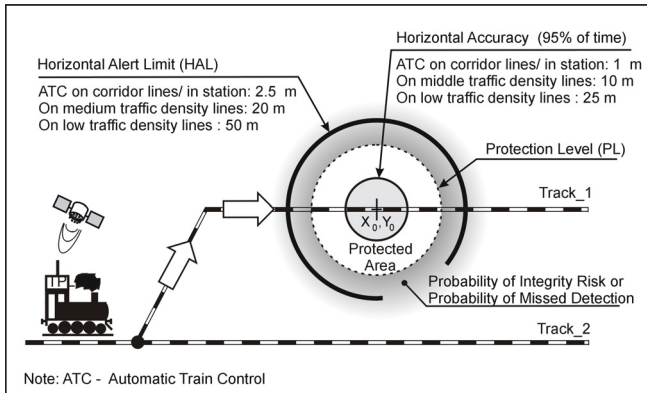
Figure 2: Sensor data validation and potential failure sources.



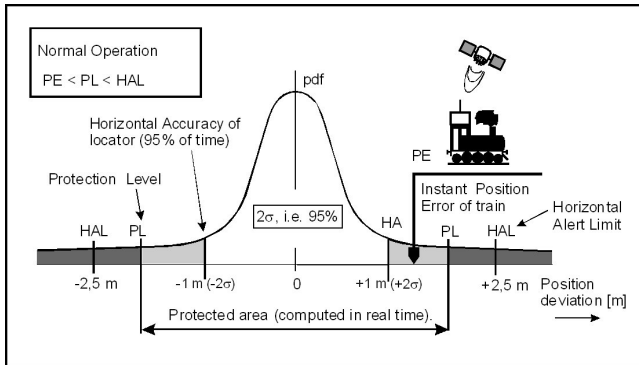
5 Autonomous integrity monitor

5.1 The basic principle

The AIM provides a guarantee of the estimated position error PE of the TPL to a user. The basic principle of the AIM is outlined in 2D space in fig. 3(a) and by means of the probability density function in fig. 3(b).



(a)



(b)

Figure 3: The basic principle of the safety integrity monitor explained (a) in 2D area, and (b) by means of pdf.

The AIM computes in real time so called protection level PL as an estimate of the position error PE , i.e. $PL = K \cdot \sigma$. The guarantee is provided by the comparing of the protection level PL with the user defined value of the horizontal alert limit HAL . The degree of the guarantee results from the required THR (i.e. required IRR or P_{MD}). K -factor depends on the specific application of TPL (train position

determination on high-traffic density line or regional lines, train routing detection on the switch, etc.) and σ results from the covariance of state estimate.

The statistical value of the horizontal accuracy HA (95% of time) is known to a user. Similarly as the K -factor, the value of HA also depends on kind of the safety related application of TPL (see table 1). However, the instant value of PE is unknown to the user. Therefore, except the normal operation state of the TPL, which is shown in fig. 3(b), the additional five states of AIM can be defined. All possible states of the AIM are summarised in the following table:

Table 3: The states of the safety integrity monitor.

	State description	Condition	Note
TPL Available <i>(PL ≤ HAL)</i>	Normal Operation	$PE < PL \leq HAL$	No failure
	Missed Detection!	$PL \leq HAL < PE$	Hazardous State!
	Integrity event?	$PL < PE \leq HAL$	PE is unbounded correctly
TPL Unavailable <i>(PL > HAL)</i>	True Alert	$HAL < PE < PL$	Safe State
	False Alarm	$PE < HAL < PL$	Too conservative bound
	Integrity Event?	$HAL < PL < PE$	PE is unbounded correctly

5.2 The integrity monitoring technique

In order to determine whether an error (bias) has occurred in the measurements, the following statistical hypothesis

$$\begin{aligned} H_0 &: \text{no failure} \\ H_1 &: \text{a failure occurred} \end{aligned}$$

(1)

and a decision test statistic T can be formulated. Then the error detection scheme can be implemented by means of a comparison of the test statistic T (i.e. decision variable) with a decision threshold T_D as follows:

$$\begin{aligned} T < T_D &\Rightarrow H_0 \text{ is accepted} \\ T \geq T_D &\Rightarrow H_1 \text{ is accepted} \end{aligned}$$

(2)

A diagram in fig. 4, which illustrates position error squared versus test statistics, shows four possible events resulting from the above hypotheses tests: *normal operation*, *true alert*, *missed detection* and *false alarm*. The probabilities of missed detection and false alarm $\{ P_{MD}=P(T < T_D | H_1) , P_{FA}=P(T \geq T_D | H_0) \}$ determine how well position errors can be detected by means of the test statistic T and the corresponding threshold T_D . These are indirectly defined in the rail user requirements in tab. 1 and 2 since the integrity risk rate corresponds to P_{MD} and the continuity of service corresponds to P_{FA} .



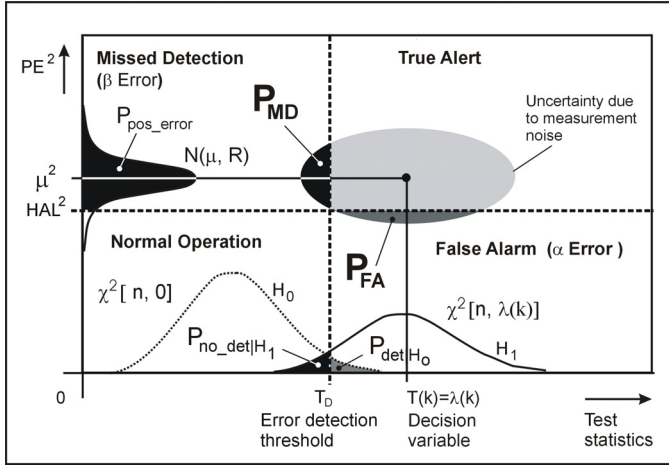


Figure 4: The graphical interpretation of the safety integrity states.

Let's consider that the KF is employed for the sensor data fusion. Then the prediction covariance measurement matrix S can be expressed as follows [5]

$$S(k) = H(k)P(k | k-1)H^T(k) + R(k) \quad (3)$$

If a bias occurs in one of the measurement or in the position prediction (see schema in fig. 2), the innovations will no longer have a zero mean, but they will become biased as well. Then the hypotheses (1) can be expressed as follows

$$\begin{aligned} H_0 \text{ (no error): } & \mathbf{v}(k) \approx N[\mathbf{0}, S(k)] \\ H_1 \text{ (error): } & \mathbf{v}(k) \approx N[\boldsymbol{\mu}(k), S(k)] \end{aligned} \quad (4)$$

where $\boldsymbol{\mu}$ is a time dependent bias in the innovations at a time step k . The test statistic T can be derived in terms of the normalized innovations squared [5,6]

$$T(k) = \mathbf{v}(k) \cdot S^{-1}(k) \cdot \mathbf{v}(k)^T \quad (5)$$

with the following distribution the hypotheses H_0 and H_1 :

$$\begin{aligned} H_0: \mathbf{v}(k) \approx N[\mathbf{0}, S(k)] & \Rightarrow T(k) \approx \chi^2[n, 0] \\ H_1: \mathbf{v}(k) \approx N[\boldsymbol{\mu}(k), S(k)] & \Rightarrow T(k) \approx \chi^2[n, \lambda(k)] \end{aligned} \quad (6)$$

where n is the degree of freedom depending on redundancy and $\lambda(k) = \boldsymbol{\mu}(k)^T \cdot S^{-1}(k) \cdot \boldsymbol{\mu}(k)$ is the non-centrality parameter. As evident from

fig. 4, the test is performed with a certain possibility of false alarm (no error), which probability $P_{det} | H_0$ corresponds to the area under the right tail of decision function $\chi^2[n, 0]$ for $T(k) > T_D$. Similarly the area under the left tail of $\chi^2[n, \lambda(k)]$ (error occurred) for $T(k) < T_D$ represents a certain possibility of missed detection, which can be expressed by the probability $P_{det} | H_0$.

The probability representing the bias μ causes miss detection is the probability of coincidence of the two following events: 1) the bias μ causes a position error and 2) the bias μ doesn't cause a detection. Then according to fig. 4, the final probabilities P_{MD} and P_{FA} can be expressed as follows

$$P_{MD} = (P_{no_det} | H_1) * P_{pos_error}, \quad P_{FA} = (P_{det} | H_0) * [1 - P_{pos_error}] \quad (7)$$

Because the test statistics is imperfect and sensor readings corrupted by a noise, false alarm and missed detection events can be never avoided. They can also never be optimized independently, thus there is necessary to make a trade-off between them. As evident from fig. 4, if the value of the detection threshold T_D is adjusted too conservatively, i.e. too low, the probability of missed detection P_{MD} in case of an error (H_1) is decreased and on the other hand the probability of false alarm P_{FA} is increased. It means that the corresponding number of hazardously misleading events is reduced but on the other hand the number of false service interruptions is increased. Therefore, the detection threshold T_D should be tuned to an optimal value which will guarantee sufficiently low rate of undetected errors and also sufficiently low rate of false service interruptions.

When the probabilities P_{MD} and P_{FA} become too large, the user cannot believe to the error detection scheme sufficiently. In this case the integrity message *Not Monitored* will occur. Therefore, the performance of the AIM can be expressed in terms of the P_{MD} and P_{FA} since these probabilities quantify the ability of the AIM to perform the error detection.

5.3 The scheme of the integrity monitor

The basic schema of the safety integrity monitor is outlined in fig. 5 and its principle is the following. The sensor readings are employed for the position estimation by a robust Kalman filter. The systematic errors (biases) resulting from the position estimation are brought to the error detector. In the error detector there is computed tests statistics including decision function $T(k)$, which is compared with the decision threshold T_D . The value of T_D is derived from the trade-off between the integrity risk (P_{MD}) and the continuity of service (P_{FA}) specified in the rail requirements. If the value of $T(k)$ exceeds the value of T_D , alert is raised ("*Not Usable*").



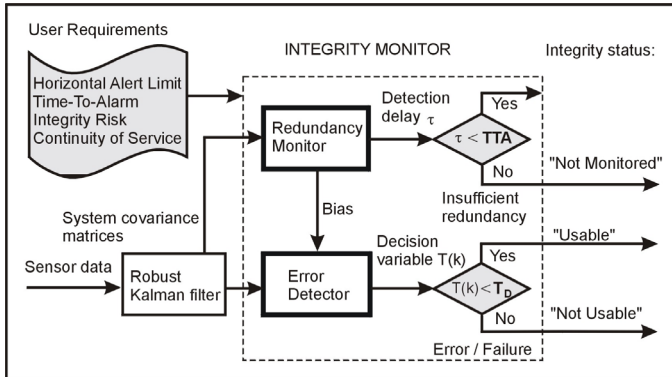


Figure 5: The autonomous integrity monitor of the TPL.

The error detection ability is monitored by the redundancy monitor. The ability depends on both the quality of measurements and the configuration of the employed redundant sensors. The redundancy monitor compares the maximum acceptable error (i.e. HAL) with the maximum value characterizing loss of precision due to exclusion of measurements (so called GiDOP [6]) in order to obtain the minimal non-centrality parameter $\lambda_{\min}$ and thus, according to fig. 4, estimate the upper bound of P_{MD} . If the P_{MD} exceeds the required value, the alert *Not Monitored* is raised. The detection delay τ , which is a function of probabilities P_{MD} and P_{FA} , can be also used for decision making instead of P_{MD} [6]. In this case, τ is compared with the user defined value of the time-to-alarm TTA (see fig. 5).

6 Conclusion

It seems that reliable GNSS/ INS based train position determination on the track or train routing detection on the switch (including absence of SIS) are not currently considered as main difficulties preventing from the application of satellite navigation in railway signalling. The recent experiments demonstrated [3,4,7] that the GNSS/INS based TPL is able to determine one dimensional position of the train with the accuracy of about 0.5 m on the track section with length of about 1 km under absence of SIS. Further it was demonstrated that after the train passed the same track section (also under SIS absence) including the switch (against the switch blade), there was possible to determine with high probability (> 0.999999) on which of the parallel tracks the train was located [7]. It should be noted that during these experiments the intentionally generated wheel slips introduced large odometry errors to the distance traveled measurements exceeding of 150 m. It means there was possible to detect the errors and correct them.

However, in order to employ the GNSS/INS based TPL in signaling and train control, there is necessary to implement an autonomous safety integrity monitor to the train position locator. The procedures enabling to build the integrity monitor represent currently one of main research interests in the Laboratory of Intelligent Systems in Pardubice.

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References

- [1] GNSS Rail Advisory Forum - Application and User Requirements, European GNSS Secretariat, May 2000.
- [2] Galileo Mission, High Level Definition, EC DG-TREN, Doc. No. I07/00050/2001, 2001.
- [3] Filip, A., Maixner, V., Taufer, J., Bažant, L. and Mocek, H.: *Fault Detection Scheme for GNSS/ INS Based Train Position Locator*, NavSat 2003 Conference, Geneva, Switzerland, June 24-27, 2003.
- [4] Bažant, L., Filip, A., Taufer, J., Maixner, V. and Mocek, H.: *Train-borne Position Integrity Monitoring for GNSS/ INS Based Signalling*. STECH'03, Tokyo, Japan, Aug. 19-22, 2003.
- [5] Bar-Shalom, Y. – Fortman, T. E. : *Tracking and Data Association*. Academic Press, Inc., Orlando, Fl., 1988, 355 pages.
- [6] Ober, P.B: Integrity Monitoring. Information Paper. No. REP9606B, TU Delft, June 1996.
- [7] Filip, A., Bažant, L., Mocek, H., Taufer, J., Maixner, V.: *Dynamic properties of GNSS/INS Based Train Position Locator for Signalling Applications*. COMPRAIL'2002 Conference, Lemnos, Greece, June 12-14, 2002.

