A Study of Integrity Indicators in Outdoor Navigation Systems for Modern Road Vehicle Applications

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Abstract— **The applicability of navigation systems in outdoor scenarios strongly depends on the level of reliability that the user can have on the provided pose estimation. For this reason, navigation systems must provide integrity values, representative of this level. In the current literature, there are two main possibilities for the provision of integrity in navigation, RAIM (or Receiver Autonomous Integrity Monitoring) and SBAS (Satellite Based Augmentations Systems) based integrity. Both options supply integrity estimators based exclusively on satellite navigation, what results in a lack of precise integrity information during absences of satellite visibility. In addition, despite the fact that modern navigation systems employ more sensors aboard the vehicle, such as odometry or inertial sensors, the methods previously mentioned do not take into account the resulting accuracy of pose estimates based on multi-sensor fusion. This paper presents a comparison between the SBAS-based HPL (Horizontal Protection Level) and HIT (Horizontal Integrity Threshold), a multi-sensor based value representative of the joint pose estimates. Real tests show its suitability to mitigate the lacks of traditional integrity indicators. The paper concludes with a revision of integrity provision in next-generation navigation systems.**

I. INTRODUCTION

The amount of vehicular services which demand positioning capabilities is continuously growing nowadays. Although vehicular telematics currently in the market provide services with positioning requirements that can be fulfilled by low-cost GNSS (Global Navigation Satellite System) receivers, the deployment of more complex road applications, such as automated toll collect systems or collision avoidance support systems, need a more reliable positioning subsystem [1]. The case of collision avoidance systems may serve as well to explain the need of further improvements in navigation. Collision avoidance support systems (CASS) are one of the most studied advanced driver assistance systems (ADAS) in the field of intelligent transportation systems (ITS). With the aim of decreasing the number of deaths and injures caused by traffic accidents, CASS developments aim to improve the traffic perception. These systems are designed to detect oncoming collisions and warn the user with enough time to make an evasive manoeuvre, or directly perform an automated control action. From a classical point of view, a collision avoidance system is in charge of estimating the safety distance to the surrounding vehicles and warn the driver in case of danger. Radar and vision based systems are in this case the most common information sources used by the subject vehicle in autonomous collision avoidance systems, and no special requirements are demanded from the navigation subsystem of the vehicle [2]–[5]. However, there is a growing interest in the research community in the so called cooperative CASS (CCASS). In these systems, vehicles share useful information by means of wireless communications in order to know the kinematic state of nearby vehicles anytime and being capable to infer potentially dangerous situations [6]–[8] . Unlike the classical approach, precise pose estimate is essential in these systems, due to the fact that trajectory intersections and possible collision forecasts are based on the poses [9], [10]. Furthermore, navigation systems installed in these vehicles should provide an indicator of the level of reliance (integrity) that the user may expect from the navigation system anytime. Since the integrity value may change depending on the environmental conditions, it is important to notify the user the actual capabilities of the CCASS.

In navigation, integrity may be defined as the capability of the system to detect performance anomalies and warn the user whenever the system should not be used [11]. An approximation to provide integrity in GNSS-based navigation is given by the Receiver Autonomous Integrity Monitoring (RAIM) algorithm. This technique, initially created for aerial navigation, is based on an over-determined solution to evaluate its consistency, and therefore it requires a minimum of five satellites to detect a satellite anomaly, and six or more to be able to reject it [12]. Unfortunately, this cannot be assumed in usual road traffic situations, especially in cities [11]. In addition, the RAIM method makes the assumption that only one failure appears at the same time at the receiver. While this assumption may be easily accepted in the aerial field, the scenario is very different in the road sector, in which a vehicle drives in very different conditions. For instance, in the very usual case of one car driving through the city center of any medium size European capital, it is quite probable that several satellite signals are affected by simultaneous multi-path propagations. Since RAIM does not consider this possibility, its integrity test may easily fail when it appears.

Satellite Based Augmentation Systems (SBAS), such as

EGNOS (European Geostationary Navigation Overlay Service) or WAAS (Wide Area Augmentation System), offer nowadays a more suitable integrity calculation. By means of the information of the GNSS operational state, broadcasted by GEO satellites, it is possible to compute a meaningful parameter of navigation system integrity [13], [14]. However, due to the fact that the source of the integrity information comes from satellites, lacks of coverage imply the absence of updated integrity measurements. Moreover, the same assumption done in the RAIM technique of only one failure at the same time is also done in this approach, with consequently the same limitations at that respect [15].

In applications such as CCASSs, where continuous positioning is mandatory independently of the environmental circumstances, assistance sensors are employed to assist GNSS sensors in the navigation [11], [16], [17]. The calculation of confidence estimators that take into account the joint performance of the multi-sensor system may supply benefits to these applications [18].

In this paper we present some of our investigations to evaluate the capability to efficiently monitor the navigation integrity of a road vehicle by means of two methods: the SBAS based HPL (Horizontal Protection Level) parameter, and the proposed HIT (or Horizontal Integrity Threshold), the calculation of which depends on the sensor variances and the covariance of the state anytime. The idea of using the estimates of the state covariance to evaluate the quality of the pose represents the basis of the Kalman filters [18], [19]. It is a common task for the researchers to analyze their values in the tuning process of the data fusion filter. Following this principle, it is possible to base the integrity of the navigation on the position variances of the state of one extended Kalman filter, as it is shown in this paper.

For that purpose, field tests were carried out in the facilities of the University of Murcia, and the conclusions of these results are next presented. These conclusions are in accordance with some interesting alternatives for integrity provision of the current literature. In [22], a combined GNSS/DR system is employed to calculate an integrity parameter capable to overcome some of the traditionally GNSS-based integrity indicators. Le Marchand et al. in [15], propose a Kalman filter based algorithm for integrity performance evaluation, and compare it with the RAIM technique, obtaining good results. Hewitson et al. in [23], also employed Kalman filters to effectively detect outliers in a kinematic GNSS positioning and navigation system. However, some other authors still rely on exclusively GNSS-based integrity, and support its use in an electronic toll collection system [24].

The rest of the paper is organized as follows. Section II describes the SBAS-based integrity calculation method followed in our architecture and Section III explains the sensor integration technique used to improve the system performance. The system prototype and the results obtained from our tests are shown in Section IV. Finally, Section V concludes the paper and analyzes the literature and future aspects of the integrity in navigation.

II. SBAS INTEGRITY

SBAS architectures, such as the American WAAS and the European EGNOS, are currently providing differential corrections to users in order to improve the position accuracy. There are three types of corrections which are continously sent to users: fast term corrections, long term corrections and ionospheric corrections. Fast term corrections are used to mitigate rapidly changing errors, such as satellite clock errors. Long term corrections treat more stable deviations, such as atmospheric and ephemeris errors. Finally, ionospheric corrections try to minimize the effect of the ionosphere in the transmission of satellite signals. Jointly with each type of correction, SBAS provides error information which can be used to compute the HPL and VPL (Vertical Protection Level) parameters, which measure the position integrity in the horizontal and vertical planes, respectively.

II-A. THE PROTECTION LEVEL CONCEPT

Fig. 1 illustrates the usage of the horizontal integrity in terrestrial navigation. A vehicle goes through the true path, but the navigation system estimates a different trajectory at a particular stretch. The difference between the erroneous and correct position at this point is the horizontal position error (HPE). Here the HPL parameter is vital in order to bound the confidence area of the position provided by the GNSS sensor. The HPL gives a good estimation (i.e. $10^{-7}/\mathrm{hour}$ probability) of the system reliability on the fact that the true position is within a circle around the computed position. The horizontal alert limit (HAL) can be defined as a proper upper bound for the HPL value. If $\mathrm{HPL} > \mathrm{HAL}$ the integrity alarm is triggered and the application which uses this information has to consider the position as not reliable. Both HPL and VPL are commonly named $\mathrm{HPL}_{\mathrm{SBAS}}$ and $\mathrm{VPL}_{\mathrm{SBAS}}$, in order to distinguish between the SBAS-based computations and the RAIM integrity factors.

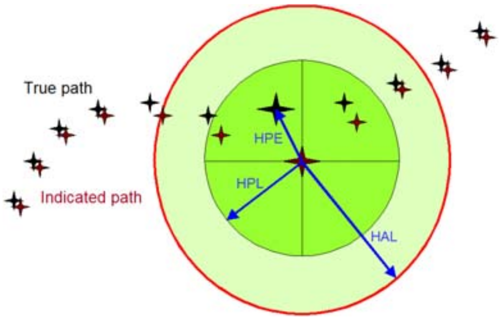

Fig. 1. Application of HPL over terrestrial navigation.

As can be noted, the horizontal plane has been especially considered through the $\mathrm{HPL}_{\mathrm{SBAS}}$ factor, due to the fact that our interest lie on vehicular navigation; however the calculation of the $\mathrm{VPL}_{\mathrm{SBAS}}$ one is direct, because the error estimations used are the same.

II-B. HPL COMPUTATION

Following [20], the final equation that we use to compute the $\mathrm{HPL}_{\mathrm{SBAS}}$ value is (1). The K_H constant depends on the level of precision required from the positioning subsystem, and is fixed by the algorithm. The d_{mayor} term depends on the geometry of the satellites used for calculating the position and the error variance of the pseudorange measurement to each satellite used (σ_i^2).

$$HPL_{SBAS} = K_H \cdot d_{mayor} = 6{,}18 \cdot d_{mayor} \tag{1}$$

The errors considered in the final estimation of the variance measurements for each used satellite (σ_i^2) can be seen in (2). Here, σ_{flt}^2 is the error variance caused by the imprecisions in slow and fast corrections, σ_{UIRE}^2 is the error variance caused by ionospheric effects in the transmission of satellite signals, $\sigma_{i,tropo}^2$ is the error variance caused in a similar way by the troposphere, and $\sigma_{i,air}^2$ is the error variance caused at the user edge. The last two parameters are not given by SBAS messages. The $\sigma_{i,tropo}^2$ factor is calculated following the tropospheric model given in [20]. The $\sigma_{i,air}^2$ calculation method is left to the user edge, and the followed process is described in [13].

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,tropo}^2 + \sigma_{i,air}^2 \tag{2}$$

III. INTEGRITY IN MULTI-SENSOR SYSTEMS

The use of multiple sensors to support the GNSS solution in outdoor navigation is required in advanced applications. Among the different approaches of the literature, the use of odometry and inertial sensors yield excellent results in many situations [11], [17], [18]. Main benefits of using odometry and IMU as GNSS complementary sensors are:

- Provision of uninterrupted positioning, independent on the satellite visibility,
- Pose estimates at a higher frequency,
- Capacity of detecting aberrant GNSS data, due for example to multi-path propagations.

On the other hand, the accumulation of the error during the periods of GNSS absence causes positioning drifts with the time, which affects the accuracy of the final navigation solution. Consequently, an integrity value which measures the reliability of the integrated multi-sensor solution becomes necessary.

There are many different ways of fusing data coming from a set of sensors, depending for example on the fusion architecture, the applied filtering techniques or the vehicle models. Most promising results of the literature employ in one way or another Kalman filters to fuse the sensor data. The Kalman filter is a recursive least squares estimator that produces at time k a minimum mean squared error estimate $\hat{\mathbf{x}}(k|k)$ of a state vector $\mathbf{x}(k)$. This estimate is obtained by fusing a state estimate prediction $\hat{\mathbf{x}}(k|k-1)$ with an observation $\mathbf{z}(k)$ of the state vector $\mathbf{x}(k)$. The estimate $\hat{\mathbf{x}}(k|k)$ is the conditional mean of $\mathbf{x}(k)$ given all observations $\mathbf{Z}^k = [\mathbf{z}(1), \cdots \mathbf{z}(k)]$ up until time k,

$$\hat{\mathbf{x}}(k|k) = \mathbf{E}[\mathbf{x}|\mathbf{Z}^k]$$

where $\mathbf{Z}^k$ is the sequence of all observations up until time k.

It is not the intent of this paper to analyze the different alternatives of data fusion. However, this proposal for multi-sensor based integrity cannot be understood without the introduction of the multi-sensor based navigation system. For this reason, the basis of the extended Kalman filter (EKF) used in our analysis are next briefly introduced. Some other more complex filters based on multiple vehicle models interaction or unscented Kalman filters were tested, obtaining several improvements in some cases. The most common EKF was finally selected for this paper for the sake of simplicity.

III-A. PROPOSED EXTENDED KALMAN FILTER

In the case of the extended Kalman filter, the provided minimum mean square error (MMSE) corresponds, not with the original non-linear system, but with an approximation of it, with linearized navigation and observation equations around its current state. The state vector considered in this work is $\mathbf{x} = (x, y, \phi, v, \omega, a)$, representing east, north, velocity angle, velocity, yaw rate of turn, and the acceleration, in the gravity center of the vehicle. The differential equation that defines the vehicle kinematics is given by

$$\dot{\mathbf{x}} = \begin{bmatrix} (v+at)\cos(\phi) \\ (v+at)\sin(\phi) \\ \omega \\ a \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \eta_\omega \\ \eta_a \end{bmatrix} \tag{3}$$

where η_ω and η_a are noise terms representing the errors due to model assumptions of constant acceleration and constant yaw rate, calculated as random walk processes dependent on the time between samples. The filter observations are GPS east and north values (x_{gps}, y_{gps}), odometry velocity (v_{odo}), and the inertial measurements for angular rate (ω_{ins}) and longitudinal acceleration (a_{ins}). Noise parameters are fixed in the tuning process of the filter, starting from the sensor specifications with final values: $\sigma_{gps} = 3$ m/s., $\sigma_{egnos} = 1$ m/s., $\sigma_{v_{odo}} = 0{,}0198$ m/s^2., $\sigma_{\omega_{ins}} = 0{,}01038$ rad/s^2. and $\sigma_{a_{ins}} = 0{,}0996$ m/s^3. The use of different values of GNSS noise in our implementation is due to the fact that we assumed that the confidence on its value depends on the nature of the coverage anytime, being smaller when EGNOS positioning is obtained. This is a first step to understand the importance of the EGNOS corrections also for the HIT parameter. Future developments will deal with more tight fusion architectures, and a better exploitation of the EGNOS corrections.

The assumed vehicle model is a simplified bicycle model in which the orientation angles of both acceleration ($\mathbf{a}$) and velocity ($\mathbf{v}$) vectors are assumed to be equal and defined by ϕ, with rate ω. This simple model serves well to our purposes, and the employment of a more complex model does not supply any special gain in these preliminary tests of integrity indicators.

III-B. HIT SOLUTION

As it has been commented, the HIT value depends on the sensor variances and the covariance of the state anytime. Monitoring the system integrity with the HIT parameter has several advantages, as compared to the RAIM or SBAS approaches:

- It supplies uninterrupted updated integrity information, even during absences of GPS and EGNOS signals,
- Its value depends on the vehicle kinematics state anytime, and it is not affected by external factors,
- It is representative of the whole multi-sensor solution, as compared to satellite based integrity.

On the contrary, its main disadvantages can be:

- It is dependent on the filter tuning process, what can make difficult the comparison of approaches with different filter adjustments,
- Since it employs the own evaluation carried by the filter to evaluate the outputs, if corrupted data are included in the filter calculation, the integrity parameter may provide aberrant information.

To cope with the first disadvantage, one possibility for filter designers may be the use of state of the art methods for filter tuning, such as NEES (Normalized Estimation Error Squared) or NIS (Normalized Innovation Squared), as representative values of its quality. Their calculations may be found in [21].

The second circumstance can be more problematic, since the whole correct functioning of the navigation system can be affected. To avoid it, the filter needs observation tests, such as the well known Mahalanobis [21]. The level of permissiveness of these tests should be very low (in the order of 10^{-7}), in order to avoid any potential risk of corruption in the filter. This has the benefit that in case one GPS position is erroneously rejected, although the accuracy of the final positioning can get worse, its integrity would stay consistent. However, in the opposite case, when an aberrant GPS location is wrongly accepted, both the accuracy and the integrity of the navigation are exposed. In addition to these tests, some other means of detecting spurious GPS measurements would be recommended.

The calculation of the HIT factor is based on the use of the state covariance matrix $\mathbf{P}$ in Kalman filters. $\mathbf{P}$ represents the level of confidence that the filters has in its own state anytime. Therefore, if we define two variables of the vector state as the vehicle position, (East and North respectively in our case), the sub-matrix $\mathbf{P}_{xy}$, detailed in (4), represents the two-dimensional quadratic form of the squared position error with 1-σ scaling,

$$\mathbf{P}_{xy} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy}^2 \\ \sigma_{xy}^2 & \sigma_y^2 \end{bmatrix} \tag{4}$$

Being σ_x, σ_y and σ_{xy} real and positive, and $\sigma_{xy} < \sigma_x, \sigma_y$, we can affirm that $\mathbf{P}_{xy}$ describes an ellipsis. The higher of the two eigenvalues of $\mathbf{P}_{xy}$, λ_{max}, can be considered as the maximum value for the horizontal position variance, and it can be calculated following (5).

$$\lambda_{max} = \frac{\sigma_x^2 + \sigma_y^2}{2} + \sqrt{\left(\frac{\sigma_x^2 + \sigma_y^2}{2}\right)^2 + \sigma_{xy}^4 - \sigma_x^2\sigma_y^2} \tag{5}$$

If we define HIT as 3-σ radius of the horizontal ellipsis around the true position, it results a 99.73 % of the fixes lying within three standard deviations (under the assumption of scalar Normal distributed errors). Therefore, HIT value can be calculated as $3\sqrt{\lambda_{max}}$. We believe that this value embraces most of the outdoor navigation applications. Nevertheless, the number of times of σ can be adjusted for more restrictive applications following the corresponding specifications. Applications such as virtual gantry based electronic toll collection, or GNSS based lane recognition require high integrity requirements, in the order of 5 times sigma. In this paper, we have assumed 3 times σ for our calculations.

Fig. 2. Test vehicle prototype based on a roadster Comarth S1-50.

IV. EXPERIMENTAL EVALUATION

In order to test the system, some trajectories have been logged with our test vehicle prototype (Fig. 2), equipped with the necessary hardware and software. The on-board equipment is composed by the IMU and GNSS sensors, the on-board computer, and a connection to the wireless network. The GNSS sensor is a Novatel GPS with EGNOS capabilities. The IMU sensor is a low cost MT9-B unit by Xsens. All sensors are connected to a Linux-based single board computer (SBC).

The data coming from the GNSS, IMU and odometry sensors are processed by the two integrity algorithms which calculate the $\mathrm{HPL_{SBAS}}$ and the HIT. The integrity information can be eventually provided to a local or remote application via wireless links.

Fig. 3 shows a comparison between the integrity values calculated along one circuit inside the facilities of our University Campus in Murcia in a 3D plot. During this test, GNSS signals were often blocked or affected by buildings, foliage, and nearby vehicles of big dimensions. As it can be seen at the first glance, $\mathrm{HPL}_{\mathrm{SBAS}}$ values suffer large variations in some stretches, whereas the HIT parameter maintains a more regular behavior. The dispersion obtained in the collected values is shown in the histogram provided in Fig. 4. The $\mathrm{HPL}_{\mathrm{SBAS}}$ parameter spreads over a big range of values, while the HIT is bounded between five and eight meters. The noticeable differences between the values extremities are due to the different definitions of the parameters. A more conservative definition of HIT, would obviously increase its final value. In addition, due to the fact that the filter reliability on its position decreases with time in absence of GNSS positions, the upper limit for the HIT value is extremely related to the duration of the GNSS absence.

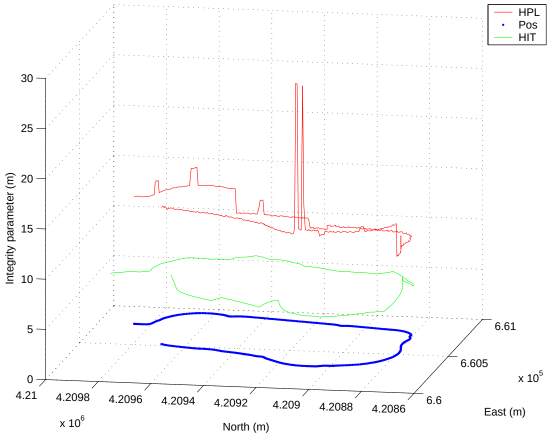

Fig. 3. HPL (red) and HIT (green) results along the trajectory (blue).

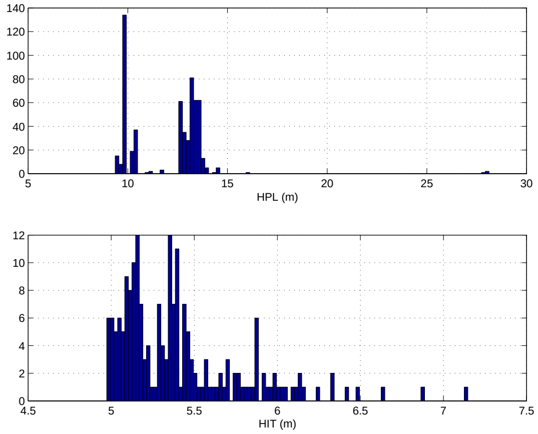

Fig. 4. Histogram of $\mathrm{HPL}_{\mathrm{SBAS}}$ and HIT values.

The results show typical problems that arise when the $\mathrm{HPL}_{\mathrm{SBAS}}$ is considered to measure the integrity of the positioning subsystem in vehicle navigation. The performance of the integrity algorithm used to obtain the $\mathrm{HPL}_{\mathrm{SBAS}}$ is seriously affected by EGNOS signal reception problems. This effect can be seen in several peaks in Fig. 3. Here, the presence of buildings, the pass through a green space, and driving near big vehicles have degraded the system performance due to visibility problems of the EGNOS satellite, provoking in the worst (and still usual) cases the total loss of a meaningful integrity value (for example, as a consequence of using non updated data in the calculation process). The problem of the reception of the geostationary satellite signal is intended to be covered by SISNeT (Signal In Space through Internet), although typical problems of cellular based communications, such as coverage and latencies complicate the timely correction. In addition to that, as it has been commented, the integrity problems due to simultaneous multipath propagations are not well represented by HPL.

Since HIT values depend on the joint multiple sensor platform, even with a complete lack of GNSS coverage, the filter can go on calculating its value. As can be seen in Fig 3, this value is clearly affected by the GNSS coverage. In periods with good GNSS coverage, the confidence of the filter location increases, resulting in lower values of HIT. According to the filtering proposed for these experiments, the HIT value depends directly on the quality of the GNSS following a simple principle, our confidence in EGNOS is higher than in a single GPS solution, and this should be represented by the integrity indicator.

In cases of satellite gaps, the HIT measurement increases, following the errors in the sensors and vehicle models. The nature of this growth will depend on the type of sensors used. For road navigation, in the normal case of employing MEMS based inertial sensors due to the budget limitations of the final OBE, it may be expected that the HIT value will follow the error curve of the sensor, rather than the vehicle model, due to the low level performance features of the sensor. In any case, if the filter is properly tuned, the HIT drifts must correspond to realistic decreases of the positioning reliability of the navigation system. Finally, it is worth remarking that during the tests, the estimated positioning errors were found within the limits of the HIT integrity indicator.

V. CONCLUSIONS AND FUTURE WORK

A study of the integrity of navigation in outdoor environments for road vehicles has been presented in this paper. Two options were developed and their results have been introduced and discussed:

- $\mathrm{HPL}_{\mathrm{SBAS}}$, based on the GPS error estimations done by EGNOS, and
- HIT, based on the sensor variances and the kinematics state of the vehicle.

The $\mathrm{HPL}_{\mathrm{SBAS}}$ parameter represents nowadays the most interesting approach to satellite-based integrity provision. However, the inherent limitations of the GNSS navigation affect its performance, resulting insufficient for some critical applications. In addition to that, the fact that the HPL concept comes from the aerial navigation constraints its capability to adequately represent integrity in roads, since some of the assumptions done in that field are not suitable for roads.

The HIT value, that defines a 3-σ radius of the horizontal ellipsis around the true position, was proposed as a safe estimator for a high number of applications, containing the 99.73 % of the fixes under the usual assumption of scalar Normal distributed errors. This parameter can be easily adapted to more demanding applications following their performance requirements in statistical terms.

According to the results achieved in our investigations, we conclude that the integrity algorithm developed by RTCA, very suitable for aviation purposes, degrades its performance in road transport applications. HIT is presented as a suitable approach to mitigate the lacks of traditional integrity monitoring.

With regard to the future of the integrity provision in navigation, we believe that it will be affected by four main aspects:

- With the beginning of the commercial operation of GALILEO, triple-constellation-capable devices will enjoy a coverage given by more than 90 satellites in orbit, with further possibilities to RAIM-oriented approaches.
- The appearance of civil low-cost multiple-frequency receivers will bring decimeter accuracy insensitive to interferences and jamming.
- The development of the MEMS technology would provide more and more accurate accelerometers and gyroscopes at lower costs, diminishing the positioning drifts during the absences of GNSS signals.
- The integration of 3D maps in the navigation calculations will help substantially to determine corrupted GNSS measurements.

Our future works in this line are intent on developing a tightly coupled fusion architecture capable to estimate more representative integrity values, as compared to the common loosely coupled INS aided GNSS implementation used in this paper.

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REFERENCES

[1] D. Obradovic, H. Lenz, and M. Schupfner, Fusion of sensor data in Siemens car navigation system, *IEEE Transactions on Vehicular Technology*, vol. 56, pp. 43–50, Jan. 2007.

[2] S. Shen, L. Hong and S. Cong, Reliable road vehicle collision prediction with constrained filtering, *Signal Processing*, vol. 86, no. 11, 2006, pp. 3339–3356.

[3] A.H. Jamson, F.C.H. Lai, and O.M.J. Carsten, Potential benefits of an adaptive forward collision warning system, *Transportation Research Part C* (in press).

[4] G. Toulminet, M. Bertozzi, S. Mousset, A. Bensrhair and A. Broggi, Vehicle Detection by Means of Stereo Vision-Based Obstacles Features Extraction and Monocular Pattern Analysis, *IEEE Transactions on Image Processing*, vol. 15, no. 8, 2006, pp. 2364–2375.

[5] A. Amditis, A. Polychronopoulos, N. Floudas and L. Andreone, Fusion of infrared vision and radar for estimating the lateral dynamics of obstacles, *Information Fusion*, vol. 6, no. 2, 2005, pp. 129–141.

[6] J.A. Misener, R. Sengupta and H. Krishman, Cooperative Collision Warning: Enabling Crash Avoidance with Wireless Technology, *in World Congress on ITS*, San Francisco, 2005.

[7] J. Ueki, S. Tasaka, Y. Hatta and H. Okada, Vehicular-Collision Avoidance Support System (VCASS) by Inter-Vehicle Communications for Advanced ITS, *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, vol. E88-A, no. 7, 2005, pp. 1816–1823.

[8] T. ElBatt, S.K. Goel, G. Holland, H. Krishnan, and J. Parikh, Cooperative collision warning using dedicated short range wireless communications, *in International Workshop on Vehicular Ad Hoc Networks*, Los Angeles, 2006, pp. 1–9.

[9] S. Ammoun, F. Nashashibi and C. Laurgeau, Real-time crash avoidance system on crossroads based on 802.11 devices and GPS receivers, *in IEEE Intelligent Transportation Systems Conference*, Toronto, 2006, pp. 1023–1028.

[10] H. Tan, and J. Huang, DGPS-Based Vehicle-to-Vehicle Cooperative Collision Warning: Engineering Feasibility Viewpoints, *IEEE Transactions on Intelligent Transportation Systems*, vol. 7, no. 4, 2006, pp. 415–428.

[11] R. Toledo-Moreo, M.A. Zamora-Izquierdo, B. Ubeda-Miñarro, A.F. Gomez-Skarmeta, High-Integrity IMM-EKF-Based Road Vehicle Navigation With Low-Cost GPS/SBAS/INS, *IEEE Transactions on Intelligent Transportation Systems*, vol. 8, no. 3, 2007, pp. 491–511.

[12] E.D. Kaplan, *Understanding GPS: Principles and Applications*, Artech House, USA; 1996.

[13] J. Santa, B. Ubeda, R. Toledo-Moreo and A.F.G. Skarmeta, Monitoring the Position Integrity in Road Transport Localization Based Services, *Vehicular Technology Conference Fall*, Montreal, 2006, pp. 1–5.

[14] G. Bacci, F. Principe, M. Luise, C. Terzi and M. Casucci, SOFT-REC: A GPS Real-Time Software Receiver with EGNOS Augmentation, *Workshop on EGNOS performance and applications*, Gdynia, 2005, pp. 1–7.

[15] O. Le Marchand, P. Bonnifait, J. Ibañez-Guzmán, F. Peyret, D. Bétaille, Performance Evaluation of Fault Detection and Exclusion Algorithms as Applied to Automotive Localisation, *Touluse Space Show. International Week on Space Applications*. (Accepted in printing process).

[16] D. Huang and L. Henry, EM-IMM Based Land-vehicle navigation with GPS/INS, *in IEEE Intelligent Transportation Systems Conference*, Washington D.C., 2004, pp. 624–629.

[17] J. Huang and H. Tan, Vehicle Future Trajectory prediction with a DGPS/INS-based Positioning, *in American Control Conference*, Minnesota, 2006, pp. 5831–5836.

[18] P.A. Boysen and H. Zunker, Low Cost Sensor Hybridisation and Accuracy Estimation for Road Applications, *in ESA Conference Navitec 2004*, Noordwijk, 2004, pp. 541–548.

[19] R. Toledo-Moreo, *A High Integrity Navigation System for Vehicles in Unfriendly Environments*, PhD. Thesis. University of Murcia, Murcia; 2005.

[20] The Radio Technical Commission for Aeronautics, *RTCA DO-229C. Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, Washington D.C.; 2001.

[21] Y. Bar-Shalom, X.R. Li, *Estimation and Tracking: Principles, Techniques and Software*, Artech House 1998.

[22] S. Feng and W. Ochieng, *Integrity Of Navigation System For Road Transport*, 14th World Congress of Intelligent Transportation Systems, Beijing, P.R.China., 2007

[23] S. Hewitson and J. Wang, *GNSS receiver autonomous integrity monitoring with a dynamic model*, Journal of Navigation, 60, pp. 247-263, 2007.

[24] M.A. Martínez-Olagüe, J. Cosmen-Schortmann, *GNSS Based Electronic Toll Collection System Of Guaranteed Performances*, 14th World Congress of Intelligent Transportation Systems, Beijing, P.R.China., 2007