Urban navigation system for automotive applications using HSGPS, inertial and wheel speed sensors

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URBAN NAVIGATION SYSTEM FOR AUTOMOTIVE APPLICATIONS USING HSGPS, INERTIAL AND WHEEL SPEED SENSORS

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BIOGRAPHY

Mariana Spangenberg is a PhD student since 2007 and her work is jointly support by TéSA laboratory and Thales Alenia Space, in Toulouse, France. She has graduated as an Electronic Engineer from the University of Buenos Aires (Argentina). Her main areas of interest are the GPS urban navigation, using dead reckoning sensors for obtaining high precision solutions.

Vincent Calmettes received Ph.D. degree in signal processing from SUPAERO (ENSAE), Toulouse, France. He is the head of the Laboratory of Electronics and Physics, at SUPAERO. His research interests include the development of solutions based on DSP and programmable logic devices or ASICs for applications in Digital communications and Signal processing. He is currently working on new Galileo signal processing and GNSS receivers architecture. He is also involved in several projects devoted to positioning and attitude determination, including low cost MEMS sensors characterization and INS/GPS integration.

Olivier Julien is an assistant professor at the signal processing laboratory of ENAC (Ecole Nationale de l'Aviation Civile), Toulouse, France. His research interests are GNSS receiver design, GNSS multipath and interference mitigation and GNSS interoperability. He received his B.Eng in 2001 in digital communications from ENAC and his PhD in 2005 from the Department of Geomatics Engineering of the University of Calgary, Canada.

Grégoire Duchâteau is graduated from the Aeronautic and Space Engineering school "Supaero" in Toulouse (France). He worked for Alcatel that he joined in 1991 and where he has worked in several areas related to fault tolerance, supervision and control for both wireless telecommunication and transport (rail, road, space) applications. Since 2003 he is technical manager of the Transport solution developed by the navigation business unit of Thales Alenia Space France and is in charge of the technical roadmap of the Multiservice Tracking Platform product.

ABSTRACT

Land vehicle navigation in urban areas, where masking effects are very frequent, is a major challenge for both the accuracy and the integrity of GPS-only solution. Several strong effects linked to urban canyon environments can seriously degrade the final position solution. Thus, the sole use of a GPS to navigate in urban areas has been proven to be challenging when high performances are expected in terms of accuracy and integrity of the computed solution.

This paper proposes a "Smooth correction function" applied to the GPS received signals. This function works on the reliability of the pseudo-range measurements when affected by diverse sources of errors. Thus, to deal with different phenomena such as multipath or low C/No signals, a merging technique between the pseudo-range and Doppler measurements is proposed.

The coupling of GPS with other positioning systems has been shown to be part of a solution to overcome satellites visibility problem in urban areas. The idea is to combine external measurements together with GPS measurements in order to improve the overall navigation system performance even during complete GPS signal outages. Dead-reckoning sensors are a classical solution to this problem. Nevertheless, due to the lack of stability of these sensors, GPS is still required to correct their correlated errors and give an absolute position when available.

Classical land vehicle navigation solutions perform GPS augmentation by using Wheel Speed Sensors (WSS) and

gyros. This paper looks at the potential benefits of a coupling approach between these two types of sensors for a complete land vehicle navigation solution. WSS provide wheel angular rate measurements and are fundamental components in the antilock braking system (ABS).

Finally, this paper introduces a multi-aided navigation system specifically designed for land vehicle navigation in urban environments. Not only sensors particularly developed for land vehicle navigation are tested, but also an interesting use of the received GPS signals (pseudo-range and Doppler) is done, leading to an optimized tight integration scheme. Test campaigns are conducted to validate the performance of the proposed integrated land vehicle navigation system. The contribution of the system is evaluated for different scenarios (urban and open areas).

INTRODUCTION

The new low-cost location technologies have rendered navigation systems affordable for many civil users. Among the fast growing GPS market, in-car navigation is becoming a leading application either for personal or professional use. However, a wide horizon of new services combining positioning systems and other already existing services is being explored. Several land vehicle positioning applications are requiring high precision solutions. The transportation of dangerous goods or road tolling are matching examples of navigation solution that requires both accuracy and integrity of the computed solution.

Navigation in urban areas appears as one of the most challenging scenarios for performing position estimations using just the GPS. In fact, the received signal will be seriously affected by different urban canyon phenomena that degrade the quality of the received signal:

- The line-of-sight (LOS) of several satellites can be obstructed, leading to potential strong reductions of the received C/N_0 and regularly to the loss of several measurements. In the latter case, this can lead to the impossibility to compute a position or to a strong value of the DOP.
- The increasing proportion of multipath that, due to strong reflection, can have an associated power close or even stronger than the direct LOS. This causes important ranging errors that will affect the position solution.
- The potential high difference of received power between obstructed and non-obstructed satellites can lead to cross-correlation problems resulting in erroneous measurements.

In the following subsections the last two effects will be referred as “measurement errors”. This generalization will be done because in real life it is very difficult to identify and separate each of these phenomena (a decrease on the quality of the signal is observed, but its specific cause can difficultly be known).

The instantaneous presence of these different sources of errors is very hard to predict and quantify, and therefore their correction is one of the main urban navigation problems. Many studies have been conducted proposing different approaches to address this problem.

The first approach proposed in this paper is the development of a HSGPS-based receiver algorithm. Having GPS signals available in normal and very noisy conditions, a position solution will be provided. The basic concept will rely on the fact that the Doppler, though it provides a correction over the velocities, should be less affected by the measurement errors than the “absolute” pseudo-range measurement [1]. Therefore, when the confidence over this latter measurement doesn’t reach a certain threshold, it will be considered to be corrupted by “measurement errors”. Then, a Doppler-smoothed pseudo-range or just the Doppler measurement will be used to correct the state vector parameters.

The decision parameter to establish the degree of confidence over the received pseudo-range measurement will be based on RAIM (Receiver Autonomous Integrity monitoring) algorithm principles [5]. The detection stage of the integrity procedure is similar to the one performed by the high precision OEM4 Inertial solution developed by Novatel [2]. However, the main difference/enhancement relies on the “exclusion” level. Once a corrupted pseudo-range measurement is detected, the corresponding GPS satellite won’t be discarded, but it will be exploited by using a different type of GPS measurement as stated on the previous paragraph. This approach is mostly suitable for urban navigation where measurements redundancy is scarce.

On the other hand, when the continuity over the tracking solution must be guaranteed, a well-known approach is to put on board dead reckoning sensors that will help the navigation filter to mainly cope with GPS outages. Dead reckoning techniques compute the actual position of the vehicle from its known initial location by integrating differential measurements. Among the most used dead reckoning systems, we find the Inertial Navigation System (INS). INS [3] are self contained non jammable systems consisting of 3D accelerometers and gyros. At the beginning this solution was restricted to the aeronautics market due to its high cost. Nowadays, with the development of low-cost sensors, such as MEMS, this solution is becoming widely spread. Nevertheless, it must be pointed out, that these sensors have low precision, so a

low-cost stand-alone INS navigation solution will have very poor performances during GPS outages.
In order to face the typical aforementioned issues, and focusing on land vehicle navigation, this paper investigates the use of the WSS (Wheel Speed Sensor). WSS are fundamental components in the antilock braking system (ABS), which is standard equipment in all new generation vehicles. WSS provide wheel angular rate measurements through the vehicle Controller Area Network (CAN). The rotation rates from different wheels can be processed to get the heading, the velocity and then the distance travelled by the vehicle. As almost all modern cars are now equipped with such sensors, their use as an alternative source of navigation may be very efficient at no additional cost. However small errors in the WSSs measurements can entail significant biases in the heading's angle calculation. A coupled WSS/gyro schema is considered an interesting navigation solution enabling the tracking of the vehicle during longer periods.

The navigation system designed and tested in the paper is composed of three parts: a High Sensitivity GPS receiver, WSSs and a gyro. All these sub-systems are integrated according to a tight coupling architecture in order to take benefit of any available measurement. The integrated navigation system is build around an adaptive central Extended Kalman Filter (EKF) capable of estimating the dead-reckoning sensors errors using raw GPS measurements (i.e. pseudoranges and Dopplers).

This paper is organized as follows: Section I presents HSGPS-based filtering algorithm using a smooth correction function that merges pseudo-range and Doppler measurements. WSSs and gyros functioning principles are explained in Section II. Section III presents the filtering coupling approaches for the navigation systems of the two previous sections. Experimental results are shown on Section IV. Finally, conclusions are drawn.

I – GPS RECEIVER ALGORITHM

TYPES OF GPS MEASUREMENTS

The three GPS measurements obtained from the receiver are:

- Pseudo-range
- Carrier Phase
- Carrier Doppler

The pseudo-range measurements provide absolute positioning but are strongly affected by multipath. On the contrary, the phase measurements provide relative positioning (the ambiguity is needed in order to calculate the present position) but have the most important advantage of being highly accurate. However, if a certain level of continuity over the GPS reception is not guaranteed, the phase measurement will be affected by cycle slips. This paper addresses the navigation problems present in urban scenarios where signals are highly interfered and GPS availability is scarce. Therefore, the carrier phase will not be considered a suitable measurement when navigating in these scenarios.

The third type of GPS measurement discussed in this paper is the Doppler measurement. Knowing the satellites position and velocity from ephemeris messages, this measurement enables the estimation of the vehicle's velocities, and hence by integration, it provides a relative position. At the same time, its most interesting advantage relies on its theoretical robustness to degraded scenarios in particular to multipath. For this approach to be valid, it is considered that Doppler measurements are not derived from the pseudo-ranges. This assumption was validated for at least one type of receiver according to [1].

Considering the aforementioned characteristics for the three types of GPS measurements, the following approach will be discussed in this paper: degraded pseudo-range measurements, mostly affected by urban canyon phenomena, may be complemented by more robust Doppler measurements. In particular, if good-visibility/low-interference GPS conditions are present, the pseudo-range measurement can be used for the position solution. Otherwise, if one of these two conditions is not satisfied, the Doppler measurement may be introduced in the measurement model.

PSEUDO-RANGE & DOPPLER MODELS

The EKF is used as the navigation filter. In eq. **(1)** and **(2)**, the filter state space model is recalled:

$$X(t) = F(t)\ X(t-1) + v(t) \tag{1}$$

$$y(t) \simeq H(t)\, X(t) + u(t) \tag{2}$$

where $X(t)$ is the state vector, $F(t)$ is the state model propagation matrix, $y(t)$ is the measurement vector and $H(t)$ is the EKF linearized non linear function relating the measurements to the state vector. The noise sequences $v(t)$ and $u(t)$ are supposed to be independent white Gaussian with covariances matrices $Q(t)$ and $R(t)$.

As concluded in the previous section, the pseudo-range and Doppler measurements are going to be used for the navigation solution. Their models are presented in equation s **(3)** and **(4)**.

$$y^{PR}{}_i(t) = \sqrt{\left[X_i(t) - x(t)\right]^2 + \left[Y_i(t) - y(t)\right]^2 + \left[Z_i(t) - z(t)\right]^2} + b(t) + w_i(t) \tag{3}$$

$$y^{DOP}{}_i(t) = -\frac{L1}{c}((V_{X_i}(t) - V_X(t)) + (V_{Y_i}(t) - V_Y(t)) + (V_{Z_i}(t) - V_Z(t))) \bullet LOS_{sat_i/veh} - \frac{L1}{c}d(t) + n_i(t) \quad (4)$$

for i=1, ...,ns, where ns is the number of visible satellites, $y^{PR}{}_i(t)$ is the pseudo-range between the user and the i[th] satellite, $[Xi(t),Yi(t),Zi(t)]^T$ is the position of the i[th] satellite in the local frame, [x(t), y(t), z(t)] is the vehicle position to be estimated, b(t) is a bias term resulting from the clock offset, and $w_i(t)$ are the measurement errors such as receiver noise, ionospheric, tropospheric and ephemeris errors. On the other hand, the $y^{DOP}{}_i$ is the Doppler shift cause by the relative motion of the vehicle with respect to the i[th] satellite, projected into the unit line of sight vector ($LOS_{sat/veh}$) between the satellite and the vehicle. The i[th] satellite velocities are denoted by $[V_{xi}(t), V_{yi}(t), V_{zi}(t)]$, the users velocities by $[V_x(t), V_y(t), V_z(t)]$, d(t) is the drift in the clock offset, $n_i(t)$ are the measurement errors, $L1$ is the carrier frequency equal to 1575.42 MHz and c is the speed of light. These equations will be used as measurement equations for estimating the desired user position.

SMOOTH CORRECTION FUNCTION

The main challenge when performing urban navigation is to reduce the positioning bias introduced by the "measurement errors". A well-known approach to deal with these problems, in particular with multipath and measurement noise, is the Hatch filter [4]. The principle of this filter is the following: the pseudo-ranges are merged with the carrier phase measurements in a recursive filter that progressively increases the weight of the carrier phase while decreasing the weight of the pseudo-range measurement. The goal of this method is to smooth the pure pseudo-range by the carrier phase measurement and eventually provide a smoothed range measurement that it is mostly obtained from the accurate carrier phase measurement. The time of transition between a highly dominated pseudo-range and a highly dominated phase measurement is given by the filter smoothing time. This convergence time is set to be superior to the correlation time of multipaths.

The Hatch filter, available in almost all receivers, can be applied if open-sky conditions insure continuity over the reception of the GPS signals (it was mainly conceived for open areas). Otherwise, as explained in the previous section, the carrier phase measurement will be affected by cycle-slips and early loss of lock in challenging environment. Hence, this filter cannot be considered a suitable solution for urban environments.

A navigation technique taking into account the approach of the Hatch filter but using a different smooth correction criterion is proposed in this paper. The robustness of the Doppler measurement is going to be exploited. A merging technique between the "absolute" pseudo-range and the Doppler measurement is proposed. The idea of assigning weights to the different GPS measurements will be addressed. In particular, the weights associated to the pseudo-range and Doppler measurements are going to be constantly calculated, and will have almost no correlation with previous sampling times. The merging expression for this approach is presented in eq. (5).

$$\boxed{y^{smooth}{}_i(t) = w_{pr_i}\, y^{PR}{}_i(t) + w_{dop_i}\left(y_i(t-1) - \frac{c}{L1}\, y^{DOP}{}_i(t)\, dt \right)} \quad (5)$$

where w_{pri} and w_{dopi} are the respective pseudo-range and Doppler weights, dt is the GPS sampling time, sub-index i denotes the i[th] satellite in line of sight, and $y_i(t-1)$ is the previous "absolute" measurement. The corresponding noise of the smoothed measurement is also a linear combination between the associated noises of the pseudo-range and Doppler measurements.
The weights will be chosen according to the values obtained from the calculation of the EKF innovation (6) and innovation covariance (7).

$$Innov = y^{PR}(t) - \hat{y}^{PR}(t) \quad (6)$$

$$Innov\_\mathrm{cov} = H(t)P_{t/t-1}H(t)^T + R(t) \quad (7)$$

where $\hat{y}^{PR}(t)$ is the estimated pseudo-range measurement from the state vector propagation, and $P_{t/t-1}$ predicted estimate covariance.

The values obtained from equation (6) and (7) will be taken as indicators of the received pseudo-range quality and therefore, of its capability to correctly estimate the position. It must be pointed out that we are going to consider as the main source of error for the filter model the incorrect calculation of R(t): neither the model associated to the state transition matrix nor to the measurements transition matrix introduce significant errors. The idea is that the pseudo-range covariance noise matrix R(t) will be constructed from the measurements noises in non corrupted scenarios. If the characteristics of the receiver and the C/No of the received signal are known, these values can be correctly estimated for typical environments. Assuming no temporal correlation in the pseudo-range measurements and no correlation among the receiver channels, the R(t) matrix will be a diagonal matrix containing the noise variance for each signal. However if the signal is affected by any kind of "measurement errors", as these are not detected a priori by the receiver and therefore cannot be quantized, the R(t) matrix will not take them into account. As a consequence, the proposed pseudo-range measurement model will be no longer valid: the associated signal noise variance will be smaller than its real value.

The principle to decide whether or not the pseudorange measurement is reliable according to the values given by eq. (6) and (7), is based on a least-square residual type method commonly used for RAIM (Receiver Autonomous Integrity Monitoring) techniques [5]. This algorithm uses an overdetermined system to perform the consistency check, where 5 satellites are needed at least to detect a faulty measurement and 6 to be able to exclude it. In urban areas, such a high visibility over the satellites constellation is very rare. Hence a RAIM approach is not a suitable solution. This paper proposes an adapted and simplified "urban integrity check". In our case, the module of *each* innovation obtained from the EKF will be compared to its associated probability distribution function and the detection and isolation will be performed simultaneously. The innovations distribution function will be characterized by a central gaussian distribution. As for the RAIM detection stage, the decision threshold will depend on the false detection probability (FDP). Using an adequate threshold criterion [6], the FDP is set to 6.33 e-5. Then the decision threshold for each i^{th} measurement will be given by:

$$\lambda^{i}_{FDP} = 4.\sigma_{innov_i} \tag{8}$$

Where σ_{innov_i} is the standard deviation associated the i_{th} filtered innovation. If this threshold is exceeded, the pseudo-range measurement will be excluded from the filtering model and will be replaced by its corresponding Doppler measurement. A second lower threshold will be statistically established to perform the so called "Smooth correction" using (5). This threshold is set to:

$$\lambda^{i}_{Smooth} = 2.\sigma_{innov_i} \tag{9}$$

Therefore, within a 2. σ_{innov_i} deviation the pseudo-range measurement will be considered totally "useful" and not corrupted. This accounts for an equivalent FDP of 0.04 (it can't be formally considered a FDP because the pseudo-range measurement won't be excluded beyond this threshold but rather merged with the Doppler measurement (5)).

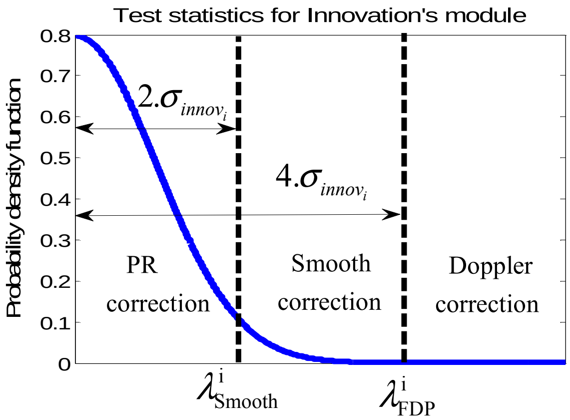

Figure 1 – Test Statistic for EKF innovation (5)

A "smooth correction function" (figure 1) associated to the reliability on the received pseudo-range measurement is proposed. If the pseudo-range filter model (associated to the calculation of R(t)) is proven not to be valid, the Doppler measurement is introduced as a complementary/alternative source of measurement.

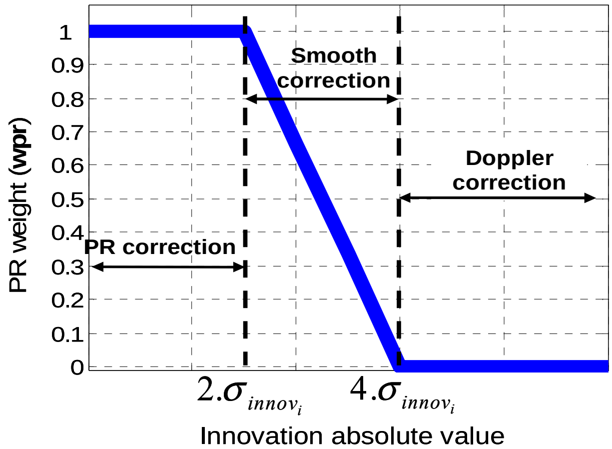

Figure 2 – PR weights associated to the Smooth correction criterion

Figure 2 illustrates the function which will determine the weight values (importance or reliability values) associated to the each pseudo-range measurement, depending on the actual ratio between eq. (6) and (7). A weight value equal to 1 indicates that the pure pseudorange is used in the filter measurement model, while a value equal to 0 means that no contribution of the pseudorange is considered. The relationship between the pseudorange and Doppler weights is:

$$w_{DOP} = 1 - w_{PR} \tag{10}$$

where the pseudo-range weight decreases linearly between 2 and 4 σ_{innov} .

The criterion for deciding which type of GPS measurement is going to be use as an input to the navigation filter is divided in three categories:

- If the innovation (eq. (6)) over the i^{th} receiver channel has a value smaller or equal to 2 times its corresponding standard deviation σ_{innov_i} (obtained from the i^{th} element of the diagonal of eq. (7)), the filtering model is considered correct, and the "absolute" pseudo-range measurement is used to correct the position.
- If the innovation over the i^{th} receiver channel has a value that is bigger or equal to 4 times its corresponding standard deviation σ_{innov_i} , the pseudo-range measurement is considered highly

corrupted, and the more robust Doppler measurement is used to correct the velocities.

- If the innovation over the i[th] receiver channel has a value that is between 2 and 4 times its corresponding standard deviation σ_{innov_i}, a "smoothed" measurement is used. This measurement is obtained from the pseudo-range smoothed by the Doppler measurement according to their respective associated weights (eq. (5)). Some particular cases for the application of this smooth correction criterion are considered in the following paragraph.

If in the previous instant (t-1) the measurement used for the i[th] receiver channel was the Doppler measurement, then there is no i[th] "absolute" measurement available for (t-1). Hence, the smooth correction expression of eq. (5) is not a possible option at time instant (t): either the pseudo-range (w_{pr}=1) or the Doppler measurement (w_{pr}=0) is used for the filtering. At the same time, for an average urban vehicle dynamics (~ 30 km/h), the multipath correlation time is considered smaller than 5 seconds, so consecutive corrections for the same i[th] receiver channel using just the Doppler measurements can be performed for a period not exceeding the 5 seconds. Indeed, if just the Doppler is used to correct the position, a divergent solution over time is obtained; therefore the pseudo-range measurement is periodically needed.

II - DEAD RECKONING SENSORS

During partial and total GPS outages the contribution of the dead reckoning (DR) sensors is crucial. They enable continuity over the position estimation, though, if left alone for a long period, they will provide highly biased solutions. However, for short GPS outages periods, they can be used as a reliable source of navigation. Moreover, as they give a priori information of the vehicle's dynamics, integrity checks as the one propose on the previous section, may become more efficient. Corrupted pseudo-range measurement are not compared to a statistical model of the vehicles dynamics, but to the solution computed from the real DR measurements. In the following subsections, two different types of automotive dead-reckoning sensors are presented.

WSS (WHEEL SPEED SENSOR)

This section describes the main elements of differential odometry. The idea is that the distance traveled and the yaw rate can be calculated using the measurements given by the vehicle WSSs. The WSS measurements will be calibrated to provide reliable information during GPS satellite outages. Figure 2 shows WSSs located on the front and rear wheels. The first index of the different variables refers to the front *f* or rear *r* axes whereas the second index corresponds to the left *l* and right *r* sides of the car. Consequently, the wheel radii (resp. angular velocities) are denoted as R_{rl}, R_{rr}, R_{fl} and R_{fr} (resp. w_{rl}, w_{rr}, w_{fl} and w_{fr}). The other notations used in figure 2 are *L* for the length between wheels and for the vehicle yaw rate (change of angle of direction). This paper focuses on velocity and yaw rate calculations using rear wheels. This choice is motivated by the fact that acceleration and deceleration have less effect on the output of these sensors.

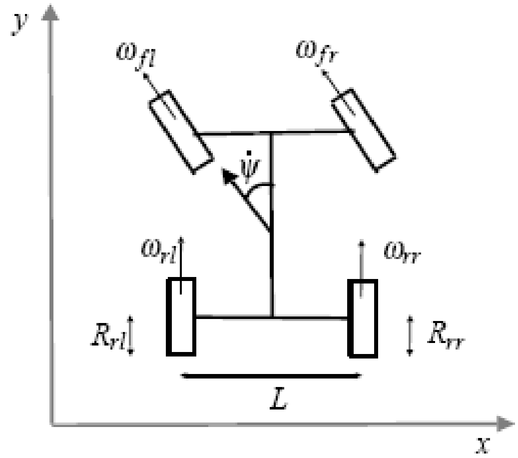

Figure 3 - Vehicle's model

Assume first that the wheel radii are constant and known. The mean speed of the vehicle (in the along track direction) at time *t* can be computed as [5]:

$$v_{along\_track}(t) = \frac{\omega_{rr}(t)\,R_{rr} + \omega_{rl}(t)\,R_{rl}}{2}. \tag{11}$$

The yaw rate of the vehicle can be calculated similarly as a function of the angular velocities of each wheel (equation 11). By neglecting side slip effects (see [7] for more details) and modeling the vehicle as a rigid body, the vehicle yaw rate at time *t* expresses as:

$$\dot{\psi}(t) = \frac{\omega_{rr}(t)\,R_{rr} - \omega_{rl}(t)\,R_{rl}}{L}. \tag{12}$$

Therefore, a two-dimension position solution can be computed using (13) (14), where the *ne* sub-index denotes the "north-east" frame. The final geodetic position (latitude and longitude) will be given by $\lambda(t) = \lambda(t-1) + \dot{\lambda}(t).dt$ and $\phi(t) = \phi(t-1) + \dot{\phi}.dt$, where dt denotes the sampling period.

$$\mathrm{v}_{ne}(t) = \begin{bmatrix} \mathrm{v}_{along\_track}(t).\cos(\psi(t)) \\ -\mathrm{v}_{along\_track}(t).\sin(\psi(t)) \end{bmatrix} \tag{13}$$

$$\begin{pmatrix} \dot{\lambda} \\ \dot{\phi} \end{pmatrix} = \begin{pmatrix} \frac{1}{R_\lambda} & 0 \\ 0 & \frac{1}{R_\phi \cos(\lambda)} \end{pmatrix} v_{ne}(t), \qquad (14)$$

Errors in the wheel radii or in the measurements given directly by the sensor will have a strong impact on localization accuracy when getting propagated through the angle and velocity expression. Indeed, any non corrected error will result in an accumulative increasing error due to the integration performed to obtain the position. By coupling the WSSs with the GPS, these errors can be reduced. Moreover, in section IV, it is shown that the precision of the yaw angle calculated from the WSS measurements is very poor. A gyroscope will be introduced to the dead-reckoning scheme, in order to enhance the navigation performance.

GYROSCOPE

Gyroscopes are inertial sensors that measure the rotation rate of the sensor cluster. By integration, the attitude angles can be calculated and the vehicle's orientation can be tracked. Using an additional sensor that delivers the distance traveled, such as the WSS, the trajectory can be computed. In this paper, a one-axe gyroscope will be used to measure the heading or yaw angle.

III - HYBRID NAVIGATION SYSTEMS

HSGPS/WSS

The common GPS/Dead-Reackoning (DR) coupling techniques use the GPS pseudo-range measurements to correct the DR errors in order to obtain reliable position estimation. The errors of the DR system are defined as the difference between the actual DR parameter values and their estimations $\delta X = X - X^{estimated}$. The state model describing the WSS errors dynamic behavior can be obtained by linearizing the ideal equations around the WSS estimates. The state vector is then augmented with systematic sensor errors:

$$x = \left(\delta\lambda, \delta\phi, \delta v_r, \delta v_l, \delta\psi, \delta\dot{\psi}, b, d\right)^T \in \mathbb{R}^8 \qquad (15)$$

where $\delta\lambda$ and $\delta\Phi$ contain the position (latitude and longitude) errors, δV_r and δV_r are the velocity errors corresponding to the right and left wheel, $\delta\psi$ and $\delta\dot{\psi}$ are the yaw angle and yaw rate errors, b denotes the GPS receiver clock offset in meters and d is its drift. The terms δV_r and δV_l represent both the WSS errors and errors in the nominal value of the wheel radius. This type of representation was chosen because these two types of errors can be considered additive and independent for each wheel. Moreover, it cannot be granted that, if treated separately, these two sources of errors are observable. The measurement equations for the HSGPS/WSS system are given by eq. (3), (4) and (5). A frame transformation must be done from the DR corrected geodetic coordinates *(λ, Φ)* to the rectangular coordinate system *(x, y, z)*. For our two-dimension navigation system, the height will be considered known.

This kind of hybrid approach can be considered as the most cost-effective scheme for automotive navigation augmented systems. However, due to the differential nature of the heading angle value (difference between the two wheels velocity), if any slipping or skidding take place, the heading angle will be affected by a very large error. A popular solution to this problem is to augment the system with a gyroscope.

HSGPS/WSS/Gyro

According to [6] and to the results shown in the next section, the calculation of the yaw rate from the WSS measurement shows serious limitations. Therefore, for the HSGPS/WSS/Gyro approach, the gyro will provide the yaw-rate and the WSSs will just be used to compute the along-track velocity. The filtering schema is very similar to the one used for the HGPS/WSS system. The state augmented vector is formed by the following parameters:

$$x = \left(\delta\lambda, \delta\phi, \delta v, \delta\psi, \delta\dot{\psi}, b, d\right)^T \in \mathbb{R}^7 \qquad (16)$$

Where the only difference with (15) is that $\delta\psi$ and $\delta\dot{\psi}$ correspond to the errors issued from the gyro, and the WSSs errors are condensed into δV (there is no need to differentiate them because to the along-track velocity they all appear as one general, additive error). For this integration approach no correlation is considered between the yaw angle error and velocity error. Alignment errors between the gyro and the vehicle's main axis are considered negligible**.**

Finally, the integrated navigation solution is presented in figure 3. Three main blocs that act as an input to the EKF may be distinguished: 2 corresponding to the different dead reckoning sensors (WSS and gyro), and the third one corresponding to the HSGPS-based receiver algorithm where the *Smooth correction criterion* is implemented.

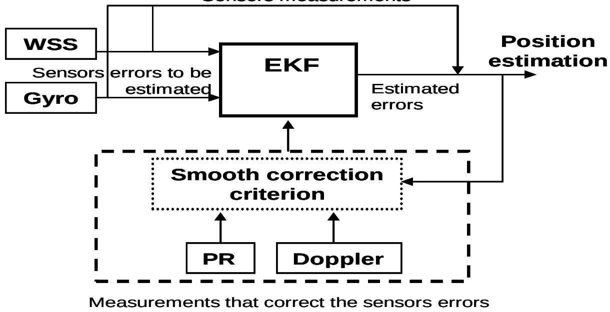

Figure 4 - Integrated navigation filter

IV - EXPERIMENTAL RESULTS

This section presents the results of the measurement campaigns conducted in order to test and validate the proposed navigation solutions. Two kinds of environments are studied: open-sky and urban scenarios. Special attention is paid to the performance of the different navigation approaches when trying to deal with corrupted signals (i.e. measurement error) or GPS outages. Firstly, the HSGPS-based approach will be tested, and later the dead reckoning sensors will be incorporated to achieve the final navigation solution.

The reference trajectories for both scenarios are shown in yellow in figure 5 and figure 6. Significant intervals of these trajectories are chosen to clearly illustrate the characteristics and performances of the different navigation filters. Intervals of 2 minutes are considered and, in particular for the urban scenario, an interval presenting dense urban canyon phenomena is chosen.

Figure 5 – Open-sky reference trajectory

Figure 6 – Urban reference trajectory

The Ublox TIM-LR GPS receiver was used. The pseudo-range and Doppler measurements were processed at 4Hz. Doppler measurements are filtered by the receiver so as not to account for instantaneous errors that could entail a highly divergent solution. The ionospheric and tropospheric errors were corrected using the Egnos messages in post-processing, simulating a real-time link obtained through a communication device. To calculate the measurement noise covariance matrix $R(t)$, the Egnos standard deviations for the atmospheric corrections were added to the computed (C/No)-based measurement errors.

Figure 7 illustrates the performances of four different navigation filtering techniques. The first one is a typical least-square (LS) approach presented here as a standard benchmark solution. The difference between the last three techniques (based on the EKF) relies on the measurement models and criterions used. For the curve in blue, a standard navigation solution using pseudorange (PR) measurements is tested. On the other hand, the *PR-Doppler filtering* and *Smooth filtering* rely on integrity controls and various measurement models. For the PR-Doppler filtering a standard single-threshold integrity check will be used. The value of this threshold is set to $4.\sigma_{innov}$. After computing the innovation from the pseudorange measurements, its value is compared to the established threshold. If the measurement is determined to be unreliable, it's replaced by its corresponding Doppler measurement. The *Smooth filtering* is based on the proposed "Smooth correction function": the principle of this algorithm is illustrated on figure 1 and 2. Two thresholds are set for this last enhanced approach and three types of measurement are used.

During the first 100 seconds of the trajectory in figure 7 all the filtering approaches have the same performance. The quality of the received pseudorange measurement is very good so no detection is computed for the integrity check. Figure 8 shows the different types (4) (5) and number of measurements used by the last two techniques at every instant, if the integrity check detects a "corrupted" pseudorange signal. For the last 60 seconds, two new satellites are in visibility with very low elevation angles and therefore very susceptible to measurement errors. Their contribution degrades the performance if no integrity monitoring is done. The *Smooth filtering* achieves the best performance by a minimum mean error and a better stability.

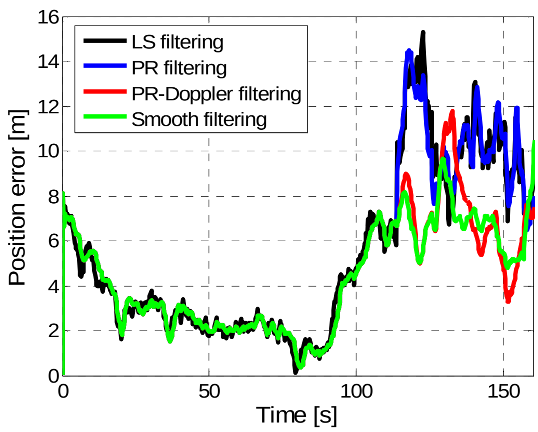

Figure 7 - HSGPS based navigation solution for open-sky scenarios

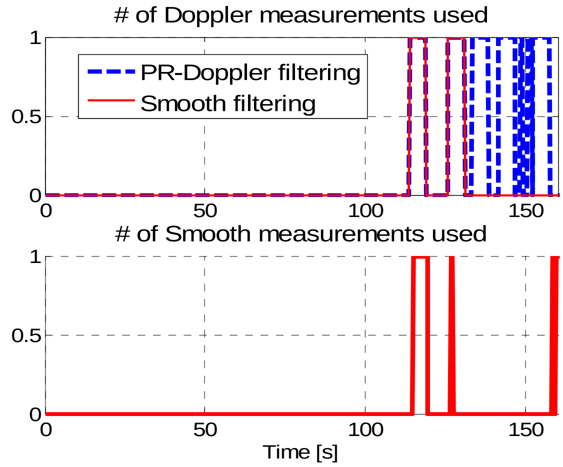

Figure 8 – Alternative GPS measurements used in open-sky scenario

The same filtering techniques are tested in an urban scenario. Evidently, for any non optimal tracking conditions (i.e. "measurement error" or GPS outages present) the LS approach can't provide a valid position solution (figure 9). Figure 10 presents just a zoomed view over figure 9 to enable the analysis of the EKF-based filtering techniques. In this case both integrity-based filters present the same results and outperformed the standard *PR filtering*. In the presence of important "measurement errors" the Doppler measurement will be directly used, so the behavior of both *PR-Doppler* and *Smooth filtering* techniques is the same. Partial GPS outages (2 or 3 satellites in line of sight), appear during a 40 seconds time interval, entailing significant position errors. The solution to this lack of measurements redundancy is to integrate additional tracking sensors to the vehicle. The final enhanced navigation solution is augmented with dead reckoning sensors as presented in Section III.

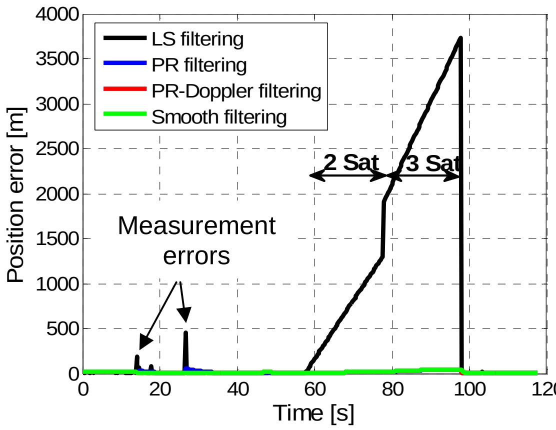

Figure 9 – HSGPS based navigation solution for urban scenario

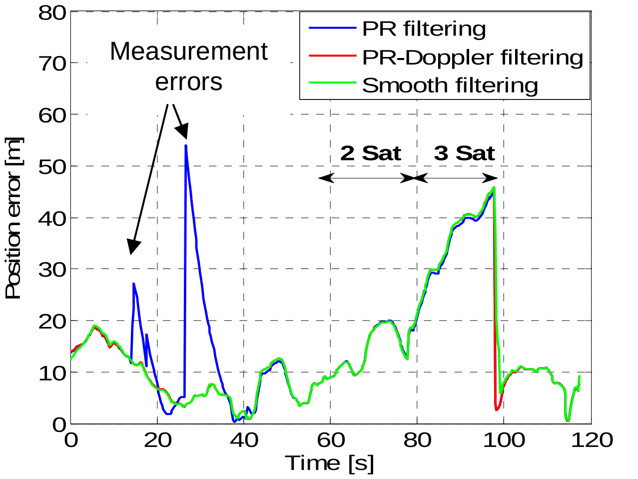

Figure 10 – HSGPS EKF-based navigation solution for urban scenario

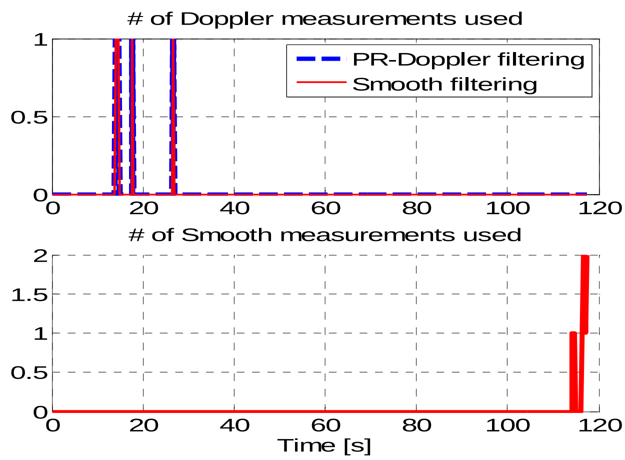

Figure 11 – Alternative GPS measurements used in urban scenario

The used WSSs were those that are already on board and that serve mainly to the ABS system. The data was recuperated through the on-board diagnostic (OBD) port using an ELM327 device (which is an OBD to RS232 interpreter). The velocity frames were produced and processed at 50Hz. For the gyro, two possibilities were explored: an already on board gyro present in most vehicles having the ESP (Electronic Stability Program) option, and an external gyro specially developed for land vehicle navigation (Melexis MLX90609). This last gyro worked at 70Hz. No significant loss of information was found when interpolating the Melexis-gyro data at 50Hz, so as to align the frequency of both dead reckoning systems. The propagation rate of the EKF was set to 50Hz following the sensors frequency. Every time GPS measurements become available, the propagated state vector (containing the position error) is corrected. Table

1 summarizes the noise values for each of the dead-reckoning sensors:

Gyro ESP	Gyro Melexis	WSS
0.2 °/s $\sqrt{HZ}$	0.02 °/s $\sqrt{Hz}$	0.08 m/s

Table 1 – Sensors noise values

The stand alone dead-reckoning position solutions are presented on figure 12. Two different integration models were tested following the principles presented on Section II. As expected for the WSS solution, where both the velocity and heading angle are calculated from the WSSs, the integrated increasing error over time strongly affected the heading angle. Hence, the interest of coupling a gyro to the system was shown. WSS+External Gyro (i.e. the MLX90609 model) was the most performing solution. Due to the poor performances obtained for the on board "ESP gyro", this integrated solution was discarded for posterior treatment.

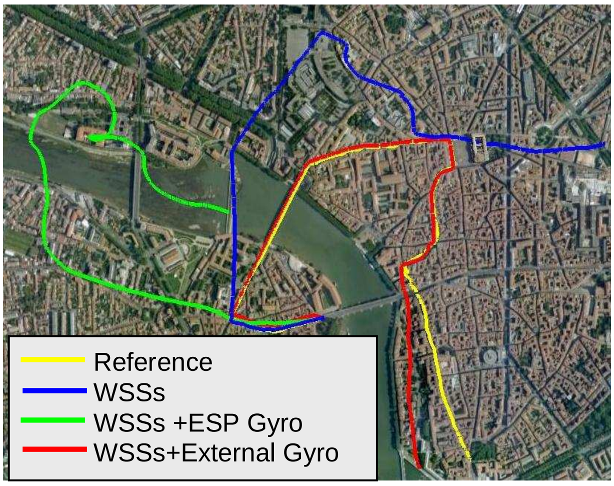

Figure 12 - Dead-reckoning navigation solutions

Finally, the complete enhanced hybrid approach was implemented. While it was already shown that the *Smooth correction criterion* was able to deal with the so called "measurement errors", the performance of the coupled dead-reckoning solutions regarding the GPS outages is especially studied. Two dead-reckoning approaches are used: the "no-additional cost" WSSs and the WSSs+Melexis gyro. Their performances are compared using the standard PR navigation solution and the proposed *Smooth* solution. As the essential contribution of this last optimized navigation scheme is focused on GPS outages problematic, just the performances for the urban scenario will be shown (figure 13). Both hybrid systems present good performances during a partial GPS outage of 3 satellites. However, for 2 satellites in visibility, only the WSS+Gyro approach continues to provide a reliable position estimation while the increasing integration error of the WSS can't be controlled.

While the implementation of the *Smooth filtering* presents better results for the WSS hybrid system, no significant contribution is observed for the WSS+Gyro approach. Basically, the WSS+Gyro schema presents a high precision in an already stand-alone configuration (fig 11). Therefore, its associated noise value is very low compared to the one of the noisy GPS signals. During the filtering correction stage, the EKF won't give a significant weight to the GPS signals but it will mainly rely on the dead-reckoning (WSS+Gyro) solution.

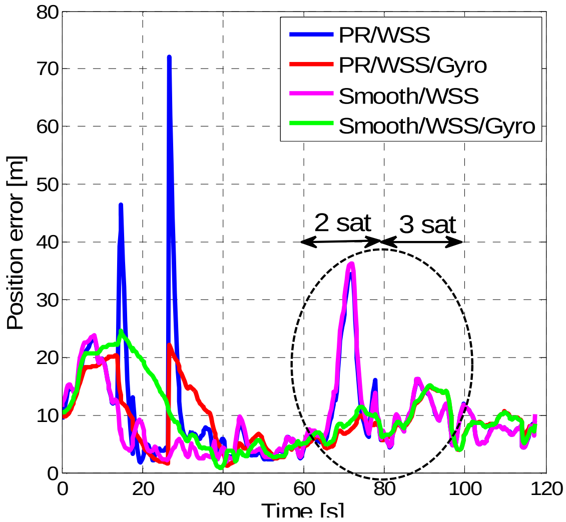

Figure 13 - Final enhanced navigation

CONCLUSIONS

This paper investigated different approaches for land vehicle urban navigation. Among the urban canyon problems two main categories were studied: the positioning errors caused by the "measurement errors" and those caused by GPS outages. To address the first source of errors, HSGPS-based receiver algorithm was proposed. A "smooth correction function" combining the pseudo-range and Doppler measurements showed very interesting results in noisy scenarios.

On the other hand, to deal with GPS outages, dead-reckoning sensors were incorporated. The ABS already on-board WSSs and an additional gyro were exploited. By using the WSSs from left and right wheels, the vehicle's distance traveled and yaw rate could be estimated. A coupled dead-reckoning system was proposed. As a consequence the navigation performance was highly improved. Experimental results showed that the final

Smooth//WSS/Gyro hybrid system is a promising navigation solution for urban environments.

Further studies should be dedicated to formalize the linear transition model between the pseudo-range and Doppler measurements. Improvements over the WSS model to include side-slipping effect should be analyzed. A field test campaign to generalize the behavior of different vehicle's WSSs is within the perspectives the authors have for this work.

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