Collaborative Vehicle Self-Localization using Multi-GNSS Receivers and V2V/V2I Communications

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I. INTRODUCTION

A reliable localization system, providing accurate vehicle positioning and orientation estimation, is a crucial component in road self-driving vehicles [1]. It has been reported [2] that vehicle heading is unobservable, in case of land vehicles relying on MEMS IMU/DGPS integrated navigation systems (INS), when the vehicle moves with only slow changes in attitude and acceleration. With the purpose of improving the heading accuracy of MEMS IMU/DGPS INS, a method is proposed in [2] which integrates in the estimation process an additional heading measurement derived from the DGPS positions. Hsu and Chan [3] proposed a multi-sensor system with three GPS-receivers, an IMU and four suspension displacement sensors in order to accurately estimate vehicle orientation and road angles in real-time. As the road angles influence the dynamic behavior of the vehicle, this knowledge can be used on rollover prevention or vehicle stabilization systems. Table I summarizes some other relevant studies addressing vehicle self-localization.

The use of DSRC (Dedicated Short Range Communications) such as standard IEEE 802.11p or WAVE, can help to overcome typical drawbacks in GNSS positioning systems [7]. DSRC systems are designed to support high velocity and low latency communication among vehicles (V2V) or among vehicles and infrastructures (V2I). In [8], vehicle localization is attained by integrating distance estimates among neighbor vehicles, inside the vehicular network. In that method, each node estimates the distance to each neighbor in the network using a RSSI (received signal strength indication) method. This information is then shared with the closest neighbors (single hop wireless network) in order to allow each node to create a map with the relative position of its neighbors. Although the simulation results give evidence that in conjunction with a GPS, this technique achieves good performance in estimating vehicle position, in more challenging environments, due to RSSI bottlenecks (noise caused by multipath sources, loss of line of sight, etc), the method may become useless.

In this paper, we introduce a novel approach for collaborative vehicle self-localization using multi-GNSS receivers and V2V/V2I communications. The results presented in this paper can be partially reproduced using ISR-CVSL toolbox. The ISR-CVSL toolbox encompasses both dataset and source code, enabling the performance evaluation of experimental results offline (available at http://www.isr.uc.pt/~conde/isr-cvsl/).

II. SYSTEM ARCHITECTURE AND SUPPORTING TECHNOLOGIES

A. System Architecture

As shown in Fig.1, the developed Cooperative Vehicle Self-Localization (CVSL) system is mainly composed by three entities: road vehicles, road side units (RSU) and

Resumo—This paper presents a collaborative self-localization approach using a multi-GNSS receiver setup and V2V/V2I communications. The purpose is to develop a low-cost alternative (equipment and installation), without compromising the process of localization estimation. The proposed method uses two GPS-receivers installed on the vehicle, disposed longitudinally on the cover (to maximize the distance among receivers) in order to estimate the Yaw and Pitch angles. To estimate the Roll angle, the proposed approach uses information from a receiver on the road infrastructure or on a nearby vehicle using V2V and/or V2I communication (compliant with 802.11p standard). Experimental results revealed that the performance on both absolute positioning and Pitch angle estimation is very high. The method is accurate in Yaw angle estimation enabling acceptable results in heading computation. Therefore the use of this algorithm in risk assessment on crossroads approaching scenarios, is achievable with an affordable setup. The Roll angle estimation can reach satisfactory results if there is a third receiver in the vicinity and in a non-collinear position with respect to the installed onboard receivers.

<table>
<thead>
<tr>
<th>Study description</th>
<th>Results/Contributions</th>
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<tbody>
<tr>
<td>An approach for vehicle attitude estimation using a GPS-receiver and a 3-axis accelerometer. EKF estimates vehicle attitude and sensor installation angles with respect to the vehicle [4].</td>
<td>This method does not require knowledge of the road tilt angle and can overcome setup offset angles.</td>
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<tr>
<td>Heading angle estimation based on LIDAR and a machine learning algorithm that relates the track surface measurements with the Pitch and Roll angles of the vehicle through a Gaussian regression method [5].</td>
<td>This approach allows a non-linear model to be learned with its accuracy depending only on the amount of extracted data. The proposed data fusion method is efficient and capable of handling fast and slow dynamics of the vehicle.</td>
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<tr>
<td>Orientation estimation system based on two GPS-receivers, IMU and an UKF (Unscented KF) [6].</td>
<td>The estimation method is able to maintain high performance even with long GPS signal blockages and to cope with cumulative errors of dead-reckoning sensors.</td>
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Tabela I: Studies addressing vehicle heading estimation

This work was partially supported by QREN-MAIS Centro and COMPETE program under project CENTRO-07-ST24-FEDER-002028.
a master antenna fixed station (MAFS). The vehicles are equipped with two GPS-receivers positioned longitudinally along the vehicle roof, a V2V/V2I communication module and a processing unit with internet connectivity. The RSU is composed by a GPS-receiver and a V2I communication module. The MAFS, which broadcasts continuously its observations to the networked agents, is composed by a very accurate GNSS receiver fixed in a well known position and with internet connectivity. The system’s main entity is the vehicle, which uses its two GPS-receivers and data from other entities to estimate its own localization. The position estimation is achieved by applying phase Double Differencing algorithm, commonly referred to as RTK (Real Time Kinematic), to the main vehicle antenna using MAFS data. Orientation estimation requires at least three non-collinear points and to maintain an affordable solution the vehicle agent has only two GPS-receivers; therefore if there is another vehicle or RSU in the vicinity, information provided by the near agent is used in the CVSL. If there are no other agents nearby, or if they are collinear the vehicle is not able to compute a new estimate of its Roll angle.

B. Multi-receiver Position Estimation

1) Standalone GNSS positioning: GPS positioning is based on signal travel time between the emitting satellite and the receiver (rover). Using the travel time, it is possible to estimate the satellite-rover distance (pseudorange). Two approaches can be used to estimate the pseudorange, code observations or carrier phase observations. Code observations exhibit higher noise levels than carrier phase observations, typically one meter to C/A (Course/Acquisition) and tens of centimeters to P (Precision) while carrier phase observations can have millimeter accuracy. Carrier phase observations require the use of more complex computational solutions since, in addition of phase offset estimation, it is necessary to estimate the integer ambiguity for each satellite [9]. An important factor in GPS positioning is the propagation medium, as the signal traverses several atmospheric layers, such as the tropospheric delay $T_r$ and ionospheric delay, $I_r$. The code observation equation is defined as follows:

$$P_r^s = \rho_r^s + c(dt_r - dt^o) + T_r^s + I_r + \nu_r^s \quad (1)$$

where $P_r^s$ is the pseudorange between satellite and rover, $c$ is the speed of light, $dt_r$ and $dt^o$ are the rover and satellite clock offsets, $\nu_r^s$ accounts for the measurement noise and

$$\rho_r^s = \sqrt{(X_r - X^s)^2 + (Y_r - Y^s)^2 + (Z_r - Z^s)^2} \quad (2)$$

is the geometric distance between satellite and rover. In (2) ($X_r,Y_r,Z_r$) and ($X^s,Y^s,Z^s$) are the rover and satellite positions in Cartesian coordinates. The carrier phase observation equation has similarities with the code equation (1); the integer ambiguity factor ($\lambda N_r^s$) is added, the atmospheric delays are multiplied by the carrier wavelength and the phase measurement noise, $\eta_r^s$, is taken into account, yielding:

$$\lambda \Phi_r^s = \rho_r^s + c(dt_r - dt^o) + T_r^s + \lambda N_r^s + \eta_r^s \quad (3)$$

where $\Phi_r^s$ is the measured offset and $\lambda$ is the carrier wavelength.

2) Double differencing GNSS positioning: by applying a single differencing process among observations of two receivers (from the same satellite), it is possible to eliminate clock drifts and mitigate atmospheric propagation delays, provided that the two receivers are close enough to assume that both are subject to the same interferences. In single differencing it is required the existence of a receiver with known position (base or master station) and a second receiver, which can be static or moving, usually referred as rover. When two receivers, $r$ (rover) and $m$ (master) observe satellites $s$ and $p$, the observation can be double differentiated, i.e. if an additional satellite is observed in the same epoch by both receivers, it is possible to make a double differencing (DD) [10]. Code and carrier phase observation equations, in DD, are respectively defined as follows:
by the same atmospheric delays, then is small enough to assume that both receivers are affected related errors. If the geometric distance among receivers ming the existence of double differencing (also denoted as secondary antennas) (e.g. \( s_1, s_2, s_n \)). With this configuration, a baseline is formed between each slave and the master antenna. Despite of being desirable that the master antenna remains static with known position, its position can be estimated by point-positioning in cases where the master is moving. Point positioning methods exhibit low precision (few meters) but this uncertainty only affects the absolute position of the system since the relative positioning method is still able to provide good baseline estimations, i.e. uncertainties associated with the master antenna position are not propagated to the vehicle orientation estimation.

1) Coordinate systems: to present the orientation estimation method, it is convenient to define two referentials: the LLF (local level frame), which is obtained by converting the ECEF (earth centered, earth fixed) coordinates of the slave antennas relative to the master and the ABF (antenna body frame) referential, formed by the GPS antennas configuration [11]. Assuming fixed baselines (distance among antennas), three antennas are necessary to form the ABF. The origin of ABF is chosen to be the master antenna position (antenna 1), the \( Y \) axis matches the baseline between antenna 1 and antenna 2 (slave antenna), the \( X \) axis is perpendicular with axis \( Y \) and it is collinear with the plane formed by antennas one, two and three and finally the \( Z \) axis is orthogonal to all others, pointing up.

2) Orientation estimation method: it is possible to map vectors or a point \( i \) from the LLF to the ABF as follows:

\[
b_i = [R_x(r), R_y(p), R_z(y)]l_i
\]  

where \( R_x, R_y \) and \( R_z \) are the rotation matrices around \( Z, Y \) and \( X \) and where \( y, p \) and \( r \) denote \( Yaw, Pitch \) and \( Roll \) (YPR) angles, and, \( b_i \) represents the position of the antenna \( i \) in ABF frame [11]. Based on the ABF definition, coordinates of antenna 2 and 3 are respectively \( b_2 = [0, b_{12}, 0]^T \) and \( b_3 = [x_{3,b}, y_{3,b}, 0]^T \) where \( b_{12} \) is the baseline between antennas 1 and 2. Introducing the ABF coordinate variables of antenna 2 in (6), yields:

\[
\begin{align*}
x_2 & = b_{12} \frac{-cos(p) \cdot sin(y)}{sin(p)} \\
y_2 & = b_{12} \frac{cos(p) \cdot cos(y)}{sin(p)} \\
z_2 & = b_{12} \frac{sin(p)}{sin(p)}
\end{align*}
\]  

Pitch and Yaw angles are directly determined from (7), however to estimate the Roll angle it is necessary the coordinates of antenna 3 (in LLF), therefore it is necessary

Figure 2: Collaborative vehicle self-localization processing modules

\[
\begin{align*}
P^{ps}_{rm} &= P^p_{rm} - P^s_{rm} \\
&= \rho^p_{rm} + \rho^s_{rm} + \lambda \Phi^p_{rm} + \lambda \Phi^s_{rm} + \nu^p_{rm} \\
\lambda \Phi^p_{rm} &= \lambda \Phi^p_{rm} - \lambda \Phi^s_{rm} \\
&= \rho^p_{rm} + \rho^s_{rm} + \lambda \Phi^s_{rm} + \lambda \Phi^p_{rm} + \nu^p_{rm} \\
\end{align*}
\]  

where \( \nu^p_{rm} \) and \( \eta^p_{rm} \) contain the noise propagation of the single observations. Accordingly to equations (4) and (5), and as long as the differencing conditions (same epoch observations, small clock drift among observations etc) are met, the double differencing process eliminates clock related errors. If the geometric distance among receivers is small enough to assume that both receivers are affected by the same atmospheric delays, then \( \rho^p_{rm} \) and \( \rho^s_{rm} \) assume very low values, making the double differencing process a very robust positioning method.

C. Multi-receiver Orientation Estimation

Orientation estimation techniques using multi-antenna configurations are based on the evaluation of inter-antenna distances (baselines) [11]. Systems using these techniques can be categorized into dedicated and non-dedicated: dedicated systems use a structure that connects all the antennas to a single receiver, in order to maintain all signals synchronized with the same clock source while non-dedicated systems are composed by different antenna-receiver pairs. The performance levels are practically identical and the non-dedicated systems are modular and generally more economical and are therefore the most popular choice between the two system categories. Assuming the existence of \( n \) receivers (Fig. 2), one of them is selected to perform as master (generally the one with the best positioning performance, the best antenna or free of multipath sources) while the others are slave antennas (also denoted as secondary antennas) (e.g. \( s_1, s_2, s_n \)). With this configuration, a baseline is formed between each slave and the master antenna. Despite of being desirable that the master antenna remains static with known position, its position can be estimated by point-positioning in cases
DD is henceforth defined by antenna (RSU’s antenna (A), menclature is used: Master Antenna Fixed Station (M) Messages), are defined in ETSI standard TS 102 637-2 [13].

These messages, designated CAM (Cooperative Awareness GCDC contain identification and localization information. IEEE 802.11p standard. The top two layers (application and presentation) are supported by CALM protocol, which developed a communication protocol based on CALM (Cooperative Driving Challenge) [12] competition it was developed a communication protocol based on CALM (Communications Access for Land Mobiles) stack protocols and ETSI standard. Wherein uses the standard 802.11p in physical and data link layers. The addressing of different nodes is carried out using MAC addresses.

The messages exchanged among network agents in GCDC contain identification and localization information. These messages, designated CAM (Cooperative Awareness Messages), are defined in ETSI standard TS 102 637-2 [13] in ASN.1 (Abstract Syntax Notation One) notation.

III. COLLABORATIVE VEHICLE SELF-LOCALIZATION

To denote the different antennas, the following nomenclature is used: Master Antenna Fixed Station (A_M), RSU’s antenna (A_{rsu}), main vehicle antenna located in the center of its rear axis (A_v), secondary vehicle antenna (A_{sv}), and finally, the main antenna of the auxiliary vehicle (A_{sv2}). The CVSL uses phase DD; for clearer reading DD is henceforth defined by $\Delta P_{m} = \Phi_{m}$. Relative positioning between antennas m and s is denoted by $mP_s$.

A. Relative Positioning

GPS-receivers provide raw data (pseudoranges, ephemeris etc) and act like the system input. In a first step, a two-level relative positioning occurs: a local DD, where the secondary vehicle antenna (A_{sv}) and the auxiliary vehicle antenna (A_{sv2}) or RSU (A_{rsu}) are each DD with the main vehicle antenna (A_v), and a global DD, where the main vehicle antenna (A_v) is DD with the master antenna (A_M). With the global DD ($\Delta P_{m}$) it is possible to estimate the absolute position of the vehicle while the local DD’s ($vmP_{vs}$, $vmP_{sv2}$ or $vmP_{rsu}$) are used to obtain the positions of secondary or auxiliary antennas relative to the vehicle’s main antenna. In order to compute the baselines between secondary and main antennas, the position of the vehicle’s main antenna is estimated by a point-positioning process. The results of this stage are: the computation of relative positions of secondary and auxiliary antennas ($vmP_{vs}$, $vmP_{sv2}$ or $vmP_{rsu}$); the position of antenna $A_v$, using point-positioning ($P_v$) and using relative positioning with the master antenna ($\Delta P_v$). Figure 2 depicts the main modules of the collaborative vehicle self-localization system.

B. Observations Processing

The DD stage provides results in a global coordinates system. For the absolute vehicle location ($\Delta P_v$), this does not constitute a problem since the majority of positioning and navigation systems use this system (latitude, longitude, altitude). However using ENU coordinate system, and choosing the tangent point (0, 0, 0) as the coordinate $P_v$ enables an intuitive and direct way of mapping all secondary antennas in the new coordinates system. This transformation allows a direct evaluation of baselines and makes the process of computing the rotation angles trivial. Figure 3a depicts the coordinates transformation performed and indicates the baselines of interest.

The baseline length $b_{ms}$, is defined as the distance between vehicle’s main and secondary antenna. The baseline length $b_{ms}$ can be used to verify the quality of a given observation, if $b_{ms}$ is too different from the real baseline between main and secondary antenna (br_{ms}), the observation is affected by large errors, which will be propagated to the self-localization phase, therefore all observations that do not comply with the the following baseline test, are discarded:

$$|b_{ms} - br_{ms}| < \sigma_{b_1}$$

(10)

The choice of the allowed tolerance $\sigma_{b_1}$ is directly related to the admissible uncertainty in $Yaw$, $Pitch$ and the real length of baseline:

$$\sigma_{b_1} = \tan (\theta_m) . br_{ms}$$

(11)
where $\theta_n$ is the maximum uncertainty associated with the $Yaw$ and $Pitch$ angles. For a 1.3 m baseline with a $\theta_n = 3.5\degree$, the tolerance value for the baseline test ($\sigma_b$) should be about 8 cm.

Regarding the third coordinate (from the RSU or auxiliary vehicle), the previous type of verification is not possible, as the baseline does not have a fixed value neither is known a priori. Still, it is possible to take advantage of the double relative positioning on the vehicle’s main antenna and auxiliary vehicle antenna or RSU $b_{nms}$). In the case of a nearby vehicle (or RSU) the communication systems exchange two types of information: the raw data of its main antennas (for local DD) and the position $M_P_{om}$. Assuming a relatively small distance among vehicles (or RSU), the baseline $(M_{b_{2m}})$ computed using $M_{P_{om}}$ and $M_P_{om}$ is expected to be similar to the baseline $(b_{2m})$ computed using local DD’s, as shown in Fig.3b. Similarly to the procedure to check $b_{nms}$, it is possible to compare the baselines $M_{b_{2m}}$ and $b_{2m}$ and check if their lengths satisfy the following condition:

$$|M_{b_{2m}} - b_{2m}| < \sigma_b$$  (12)

The threshold $\sigma_b$ is dependant of several factors like the quality of the relative positioning process, distance from vehicles to master antenna or distance among vehicles (or to a RSU), and therefore its harder to find. Given the problem of geometric constraints on accuracy, it is convenient that $\sigma_b$ values are given as a function of vehicle distances, $\sigma_b(d)$, assuming higher values when vehicles are far apart and smaller values when they are close to each other. When vehicle distances are above $d_{max}$ the $Roll$ angle is not computed. The processing module synchronizes all observations by their respective timestamp and outputs an observation matrix.

### C. Orientation Estimation

After passing the validation tests, the process of orientation estimation is trivial and follows the method discussed in section II-C. The computation of $Yaw$ and $Pitch$ angles requires only the secondary vehicle’s antenna local coordinates $v_{om}P_{vs} = (e_2, n_2, u_2)$:

$$Yaw = \arctan 2(n_2, e_2)^1$$  (13)

$$Pitch = -\arctan 2\left(u_2, \sqrt{e_2^2 + n_2^2}\right)$$  (14)

whereas for the $Roll$ angle computation, it is necessary a coordinate transformation of $v_{om}P_{v2m} = (e_3, n_3, u_3)$ as described in section II-C, resulting in $(e_3', n_3', u_3')$. After this transformation the $Roll$ angle can be calculated:

$$Roll = \arctan 2(u_3', n_3')$$  (15)

$^1 \arctan 2(Y, X) \text{ indicates a four-quadrant inverse tangent } (]-pi, pi[)$

![Figure 4: Experimental setup: (a) hardware setup diagram; (b) test environment (c) software modules and protocols; (d) test path.](image-url)
IV. EXPERIMENTAL RESULTS

A. Experimental Setup

1) Hardware setup: the ublox LEA-6T was used as both main and secondary vehicles’ GPS-receivers as well as in the RSU. This model enables easy vehicle installation, standard communication interface and provides raw-data, necessary to the phase DD. The MAFS data was obtained through SERVIR project, which consists on a military network of permanent reference GNSS stations capable of providing raw-data observations and corrections in real-time for RTK positioning or saved data for post-processing. Table II resumes the main characteristics of vehicle and master receivers.

The V2V/V2I communication is based on an optimized system for wireless routing and network security applications composed by a ALIX 2D embedded PC, a IEEE 802.11p Unex DCMA-86P2 wireless card and a external antenna Laird TRAB58003P, placed on the vehicle’s roof (see Fig.4a). The ground-truth setup is composed by a high performance GPS/IMU system Xsens MTi-G-700, capable of providing self-localization with very small errors and

Tabla II: Receiver’s main characteristics

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<tr>
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<th>ublox 6T</th>
<th>Servir - Station 9</th>
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<tbody>
<tr>
<td>Receiver</td>
<td>LEA-6T</td>
<td>Trimble NetR5</td>
</tr>
<tr>
<td>Constellation</td>
<td>GPS</td>
<td>GPS / GLONASS</td>
</tr>
<tr>
<td>Antenna</td>
<td>ANN-MS</td>
<td>Zephyr Geodetic Model 2</td>
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the RTK system \textit{TOPCON HiperPro}, capable of providing positioning solutions with millimeter accuracy.

2) \textit{Software setup}: from the software point of view, the system can be seen as an interconnection of three modules: data acquisition, V2V/V2I communications, and estimation modules, as illustrated in Fig.4c.

3) \textit{Test scenario}: the test site (see Fig.4b) allows to define a variety of testing paths (see Fig.4d), and the surrounding environment contains trees and buildings giving realism to test scenarios.

The results for V2V/V2I communications, obtained in a different location in a 1 Km straight line path without buildings or trees, show that the Round Trip Time has no correlation with distance (Fig.5a), the RTT remains relatively constant along the route with an average value of 112\,ms and standard deviation 6.45\,ms. The tests also revealed that the communication system has a good \textit{Hit Rate} performance (98\%) within a range of [0\,m; 50\,m] but decays rapidly to 50\% on a range of [50\,m; 300\,m] (Fig.5b).

The results obtained show that the proposed CVSL approach has good performance regarding the absolute position. Figures 5c and 5d show the error evolution throughout the test and Table III summarizes the mean and standard deviation errors along the test path. Errors in position are less than 0.8 m over almost all the path, the average error and the standard deviation take both reduced values.

**B. Orientation Angles Estimation**

In the orientation angles estimation, the assigned values were $\sigma_{b1} = 15\,cm$, $\sigma_{b2} = 1m$ and a maximum distance of $d_{\text{max}} = 25m$ for Roll angle estimation. As consequence, there are long periods of time where the validation module filters observations, preventing the CVSL to provide full self-localization. Figures 6(a,d) and 6(b,e) present the results obtained as concerns $\text{Yaw}$ and $\text{Pitch}$ angles respectively. The results show that the CVSL attains good performance on the $\text{Yaw}$ angle estimation and a very good performance on the $\text{Pitch}$ angle estimation. The $\text{Yaw}$
angle achieves an average error of 8 degrees. The first 80s were discarded from the average computation, since the ground-truth system had not been able to compute the proper sensor’s orientation. The CVSL is faster to converge to the real position while the system used as ground-truth, which uses an EKF, takes more time to converge to the real position. This can be easily observed on the interval [80, 240] seconds. Due to smoothing on both ground-truth and CVSL, on U-turn transitions a small time offset can generate peak errors; these were also filtered. Therefore the absolute position error is in fact lower than the computed one, since the ground-truth system does not behave properly in U-turn transitions. It is noticeable in both Figs.6(a,d) and 6(b,e) that the system sometimes fails to provide estimates, due to the restrictive nature of the validation filters.

The Roll angle estimated by the CVSL is only valid under the assumption that the vehicles are on the same plane. The developed system only estimates the Roll angle when the vehicles are close, so that the vehicles are on the same plane. When vehicles are disposed along a straight line, i.e. in situations where the auxiliary point for the calculation of Roll is nearly collinear with the vehicle antennas, the CVSL is extremely sensitive. In this situation, as the results illustrate, any noise causes large variations in the Roll angle estimates. This happens because the geometry of the set of receivers is very close to reaching a singularity (when the three receivers are collinear). One possible solution to overcome this problem would be to only compute the Roll angle when vehicles were nearly orthogonal. Figure 6(c,f) shows the results obtained in the process of Roll angle estimation along the test path. In order to facilitate the data analysis, it was introduced the distance among vehicles (dashed black).

When the geometry of the receivers tends to be collinear, it is noticeable that the Roll angle estimates tend to take extreme values, i.e. when the vehicles are crossing close to one another, the value of Roll reaches extreme values: either positive, instants before the crossing, or negative in the next instants after crossing each other. This fact leads to a very poor system performance and must be avoided, possibly by not using information from vehicles nearby the singularity zone. In Table IV mean errors (discarding the first 80 seconds) of the YPR estimates along the test path are shown. The CVSL’s Roll angle estimation is satisfactory when vehicles are very close and non-collinear, namely at [100,120] and [360,390], otherwise it as a poor performance, evident on the abnormal mean absolute error (see table IV).

A decrease in performance is expected in presence of nearby multipath sources such as buildings or high trees, since small positioning errors of the order of decimeters, can propagate large errors to the estimation of YPR angles. To mitigate this effect, a baseline validation system was developed, filtering the observations that may cause angle estimates with unacceptable errors. One obvious drawback arises from the fact that, in severe adverse conditions, several consecutive observations cannot fulfill the requirements and therefore are discarded. In this case, the system fails to provide the orientation angles until new observations became valid.

V. Conclusion And Future Work

This paper has introduced a CVSL approach based on a multi-GNSS receiver setup and V2V/V2I communications. This approach uses relative positioning techniques with double differencing, commonly designated RTK, and the IEEE 802.11p standard. The CVSL approach, aims to provide a low-cost alternative solution to the existing positioning systems, doing it without a severe loss of performance. The main goal, to keep the total cost of the setup low, was achieved avoiding the prohibitive costs of an automotive grade solution. As an example, the set of antennas, receivers and communication module is a fraction of the price compared with the systems used as ground-truth. The developed system proved to be able to estimate the Yaw and Pitch rotation angles and the absolute position of the vehicle with absolute admissible errors throughout the tests. The geometric limitation in the Roll angle estimation and the possible ways to avoid it have been also considered. As future work, in order to evaluate the real potential of the CVSL approach, additional testing in dense urban environment and adverse weather conditions should be carried out.

Referências