A Technology-agnostic GNSS/INS Real-time Sensor Fusion Platform with Ultra Wide Band Cooperative Distance Measurements for Terrestrial Vehicle Navigation

Javier Arribas, *Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA)*, Spain.

Mònica Navarro, *Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA)*, Spain.

Ana Moragrega, *Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA)*, Spain.

David Calero, *Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA)*, Spain.

Enric Fernández, *Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA)*, Spain.

Jordi Vilà-Valls, *Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA)*, Spain.

Carles Fernández-Prades, *Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA)*, Spain.

BIOGRAPHY

Dr. Javier Arribas is a Senior Researcher at the Statistical Inference for Communications and Positioning Dept. (SI), Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Barcelona, Spain. He received the MSc degree in Telecommunication Engineering from La Salle University in 2004, and the PhD from UPC in 2012. His primary areas of interest include statistical signal processing, GNSS synchronization, detection and estimation theory, software defined receivers, FPGA prototyping and the design of RF front-ends. He is the recipient of the 2015 EURASIP Best PhD Thesis Award.

Dr. Mònica Navarro received the MSc degree in Telecommunications Engineering from Universitat Politècnica de Catalunya in 1997 and the PhD degree in Telecommunications from the Institute for Telecommunications Research (ITR), University of South Australia, in 2002. Currently, she is the Head of the Communication Systems Division and Senior Researcher at the Centre Tecnològic de Telecomunicacions de Catalunya. Her primary areas of interest are on digital communications and information processing with applications to wireless communications and positioning.

Dr. Ana Moragrega holds the position of Researcher at the SI Dept., CTTC. She received the MSc degree in Electronic Engineering from the UB in 2004 and the Ph.D. at the Department of Signal Theory and Communications of the UPC in 2016. Her current research interests include positioning, Wireless Sensor Networks, UWB, GNSS and statistical signal processing. Also she has interest in digital signal processing.

Mr. David Calero holds a M.Sc. in Telecommunications Engineering from the Universitat Politècnica de Catalunya. Since 2007 he has participated in several research and industrial projects developing HW/SW prototypes related to Geomatics. The

main expertise is related to multi-sensor fusion techniques for trajectory determination, indoor mapping and image processing applications.

Mr. Enric Fernández holds an M.Sc. in Telecommunications Engineering. He works as a researcher at the CTTC Geomatics division and has mainly work in the development of mobile or portable hardware systems and in their data acquisition and normalization for the computation of INS/GNSS localization (TPVA) solutions. Thus, his main research field is in INS/GNSS data fusion for high precision, in example for dead-reckoning scenarios using high stability oscillators . Moreover, he has extended his research to the image processing field, fusing visual odometry data to the INS/GNSS solution, SLAM (localization and mapping), developing an analytical image stabilization algorithm or generating vegetation indexes (for Precision Agriculture field).

Dr. Jordi Vilà-Valls is a Senior Researcher at the Statistical Inference for Communications and Positioning Dept. (SI), Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Barcelona, Spain. He received the PhD degree in Electrical Engineering from Grenoble INP (INPG), France, in 2010. His primary areas of interest include statistical signal processing, estimation and detection theory, robust and computational statistics; with applications to positioning systems and communications.

Dr. Carles Fernández-Prades holds the position of Senior Researcher and serves as Head of the SI Dept. at CTTC. He received a PhD degree in Electrical Engineering from Universitat Politècnica de Catalunya (UPC) in 2006, Barcelona, Spain. His primary areas of interest include statistical and multi-sensor signal processing, estimation and detection theory, and Bayesian filtering, with application in communication systems, GNSS and software-defined radio technology.

ABSTRACT

This paper presents an enhancement of the well-known GNSS/INS sensor fusion approach by supporting cooperative distance measurements to improve its positioning performance for terrestrial vehicle navigation. The areas of improvement are those where the GNSS signals are severely degraded and the low-cost INS system can not provide reliable dead reckoning position estimations. In the proposed cooperative positioning scheme, additional information is acquired from other infrastructure or communication network, such as adhoc sensor network with several intercommunicated vehicles or nodes. The additional information provided mainly by distance measurements between nodes and from nodes to other elements of the network (e.g. anchor nodes placed on fixed equipment such as traffic lights) can be used as independent measurements reporting new information to the Bayesian filter. The implementation has been tested in a representative field test by deploying a network of commercial off-the-shelf Ultra Wide Band (UWB) anchor nodes, which can provide down to centimeter distance measurement accuracy. Results show an improvement of the positioning performance in challenging scenarios where the original GNSS/INS fusion did not meet ITS positioning requirements due to the GNSS signal impairments and the lack of stability of low-cost IMUs.

INTRODUCTION

Precise and accurate terrestrial vehicle positioning (i.e. lane identification) is an enabling feature for the deployment of many Intelligent Transport Systems (ITS) applications, such as automatic collision avoidance systems. Global Navigation Satellite Systems (GNSS) combined with aiding systems providing local information (Space-based Augmentation System (SBAS) like WAAS or EGNOS [1, 2]), Differential-GNSS (D-GNSS), assisted GNSS (A-GNSS) [3], and real-time kinematic (RTK) GNSS [4] is the preferred technology in outdoor environments for precise, everywhere positioning, and to a great extent one of the most accurate sources of position information when it is available. However, GNSS performance and even its availability still depend on the particular signal propagation conditions, such as multipath conditions, unintentional or intentional (jamming) interferences, and direct visibility of satellites, among others. The urban canyon represents one of the most challenging scenarios for GNSS positioning. However, such scenarios will frequently be representative for urban ITS services, where users usually require the highest accuracy.

With the blossom of low-cost Inertial Measurement Units (IMUs) in recent times, based on microelectromechanical systems (MEMS) technology [5, 6, 7], it is possible to enhance the performance of the positioning system by coupling a GNSS receiver with an Inertial Navigation System (INS). Whereas an INS provides accurate acceleration and angular velocity (and thus position) measurements, it has an inherent error that increases over time because of the sensor biases. On the other hand, the geometrical-related measurements (provided by GNSS) are typically unbiased but noisier than those of an INS. Therefore, proper data fusion of GNSS with an IMU brings the best of both worlds: reduced variance and unbiasedness.

The GNSS/INS loosely and tightly sensor fusion strategies were explored by the authors by designing and implementing a low-cost prototype in [8], tested and deployed in a measurement campaign in Helmond-Eindhoven (Netherlands) in the framework of TIMON project [9]. The selected scenario included both open sky inter-urban roads and dense urban areas. Results showed that the overall performance of the positioning system was improved. However, in deep urban canyons with strong multipath or in total blockage of GNSS signals, the INS integration did not meet the performance required by the ITS systems, mainly due to the instability of the INS sensors bias along the time. Unfortunately, even a short GNSS outage (i.e., no visible satellites) of less than 2 seconds can induce a positioning error of tens of meters.

In the one hand, in standalone GNSS-based solutions, each vehicle individually estimates its own location with GNSS/INS fusion techniques. On the other hand, in a cooperative positioning scheme additional information acquired from other infrastructure or communication network, such as adhoc sensor network with several intercommunicated vehicles (a.k.a nodes) [10, 11]. The additional information provided mainly by distance measurements between nodes and from nodes to other elements of the network (e.g. anchor nodes placed on fixed equipment such as traffic lights) can be used as independent measurements reporting new information to the Bayesian filter. Such network of mobile and fixed nodes can be deployed in the most challenging areas of an urban canyon or even inside tunnels or buildings.

In this work, we expanded the GNSS/INS sensor fusion platform to support cooperative distance measurements using a technology-agnostic algorithm. The implementation has been tested in a representative field test by deploying a network of commercial off-the-shelf Ultra Wide Band (UWB) anchor nodes, which can provide down to centimeter distance measurement accuracy. The UWB anchors were placed at known locations to enhance positioning coverage in a urban canyon for vehicular users. A mobile node was placed in a vehicle equipped with a low-cost GNSS/INS sensor fusion prototype. The mobile node delivers real-time distance measurements from the vehicle to the anchor nodes in view and the implemented algorithm fuses them with the GNSS pseudoranges (if available) and the INS data using an adaptive extended Kalman filter. The vehicle reference attitude and position was obtained using a navigation-grade GNSS/INS equipment.

Results show an improvement of the positioning performance in challenging scenarios where the original GNSS/INS fusion did not meet ITS positioning requirements due to the GNSS signal impairments and the lack of stability of low-cost IMUs. By deploying 7 UWB autonomous (battery-powered) anchor nodes, the system delivered a lane-level position in an area of 7200 square meters.

The paper is organized as follows: Section Enhanced tightly-coupled GNSS/INS/Cooperative algorithm briefly introduces a cooperative sensor fusion algorithm and the extended Kalman filter tuning parameters. Section IMPLEMENTATION includes all the implementation details using an open source hardware and software platform (Raspberry PI3) plus a set of UWB nodes. Realistic simulation results combining real GNSS/IMU data with simulated UWB measurements are available in Section REALISTIC SIMULATIONS. Section PROTOTYPE RESULTS presents the prototype validation using real-life positioning performance measurements and Section CONCLUSIONS concludes the paper.

Enhanced tightly-coupled GNSS/INS/Cooperative algorithm

Figure 1 shows a high-level block diagram of the proposed GNSS/INS/cooperative positioning algorithm. On the right-hand side, from top to bottom there is the IMU sensor, equipped with a three-axis accelerometer and three-axis gyroscope. IMU is reporting acceleration and angular rate vectors, (f_{ib}^b, w_{ib}^b) respectively, in the body frame, producing measurements at a higher rate than the GNSS receiver (typically at 100 Hz for IMU measurements rate vs. up to 10 Hz for GNSS measurements). A strapdown integration algorithm uses each new IMU measurement to update the estimation of attitude, speed and position vectors, as the classical dead reckoning algorithm does (see i.e [7]).

At this point, if there is a new GNSS pseudoranges set (ρ_G) and pseudo-range rates ($\dot{\rho}_G$) set measurement, (left-hand side of Fig. 1), a Kalman filter tracks the errors in the inertial estimation of attitude, speed, and position ($\delta\psi_{eb}^e, \delta\mathbf{v}_{eb}^e, \delta\mathbf{r}_{eb}^e$). In addition, the Kalman filter also estimates the bias in the accelerometer and the gyroscope ($\mathbf{b}_{acc}$ and $\mathbf{b}_{gyro}$). The cooperative information obtained by a communication device or other vehicle equipment is injected to the Kalman filter as an independent measurement set, as a new set of range estimations to a set of a static or dynamic anchor nodes. In Fig. 1 this is represented as the cooperative receiver box. The cooperative information provided for each cooperative positioning node is:

- **Node range estimation** ($\hat{\rho}_c$): the cooperative communications equipment measures the range between the vehicle's antenna and the smart city nodes (e.g. smart traffic lights, communication towers, etc) or measures the range to other vehicles or road users. The technology used by the equipment has no effect on the algorithm structure but should be used to adjust the filter parameters.
- **Measurement covariance** ($\hat{R}_c$): every range measurement must have an associated covariance which can be derived using the received signal parameters. The receiver' SNR can be used to estimate the range measurement covariance. This

Fig. 1. Tightly coupled GNSS/INS/UWB fusion algorithm

information is especially important for the positioning algorithm in order to give the optimum weight to each information source. If a dedicated range measurement equipment is used (e.g. an UWB range measurement device), the manufacturer also provides a custom algorithm or indication of the range measurement error.

- **Node position estimation (r_c^e):** In case of static nodes (referred to as anchor nodes in the literature), the node position is obtained by using a pre-defined database, available for all the ITS users. A cloud server can be used to distribute such database among the trusted users. This is the typical situation in a Vehicular to Infrastructure (V2I) scenario. In the presence of dynamic nodes, as in the Vehicular to Vehicular (V2V) scenario, each node must exchange its position estimation along with the associated position uncertainty. In the proposed Bayesian filter, this information is stored in the trace of the state covariance matrix $\mathbf{P}$.

IMPLEMENTATION

In this work, the positioning prototype introduced in [8], shown in Fig. 2, was extended by implementing the following new features:

- **UWB node driver:** we added a custom driver to communicate with the DecaWave MDEK1001 and EVK1000 nodes by using the USB connection to the Raspberry PI3. The driver configures the node and triggers the periodic read of the distances to the anchor nodes in range. The UWB network configuration is automatically managed by an anchor node pre-configured as the *initiator*. For more information regarding the DecaWave UWB network and protocol, the reader is referred to [12].

Fig. 2. Raspberry PI3 positioning prototype platform equipped with a GNSS receiver and dual IMUs (see [8] for more information).

Fig. 3. DecaWave EVK1000 and MDEK1001 nodes.

- **Kalman filter extension:** we modified the tightly-coupled realtime algorithm C++ implementation to accept the new UWB distance measurements and its configuration parameters such as the covariance matrices and the anchor node position database reading.
- **Cooperative sensor logging:** a GNSS time synchronized logging was implemented to store the UWB distance measurements in local log files in order to enable the analysis and the post-processing.

Figure 3 shows a picture of the EVK1000 and MDEK1001 nodes. The second version (MDEK1001) includes an on-board battery and a protective case, which facilitates the anchor node deployment. The node driver and the logging features were verified by an outdoor dynamic test where a vehicle containing the positioning prototype and the mobile node was moving towards an anchor node, located in the line of sight. The reference position was obtained from a commercial-grade GNSS receiver. Figure 4 shows a plot of the UWB measured (logged) distance versus the reference distance obtained using the vector module from the anchor node position to the GNSS position estimation. Both distances were aligned and no outliers were detected, thus, confirming the correct synchronization of the UWB readings.

Fig. 4. DecaWave MDEK1001 distance measurement plot vs. reference distance measurement.

REALISTIC SIMULATIONS

The validation of the proposed cooperative positioning algorithms and its performance evaluation required the development of a custom simulation environment. In [8] a custom simulator capable of simulating both the IMU measurements and the GNSS measurements for arbitrary trajectories was developed and tested. This simulator has the capability of using real measurements captured by the positioning prototype, showing the real-life impairments in the worst case positioning scenarios, such as the urban canyon and the GNSS-denied environments. The goal in this work is to use real measurements for all the available sensors and simulate only the cooperative positioning infrastructure of the smart city. In this way, it is possible to fairly evaluate the performance improvement of the cooperative positioning techniques in realistic scenarios. Next section provides detailed information of the modifications introduced in the simulator, the testing scenarios and the performance results.

Hybrid real data / cooperative simulation framework

Figure 5 shows the simulation framework high-level block diagram. From top to bottom, the cooperative node positions are loaded from a KML file written by Google Earth. The simulator user can set up an arbitrary number of nodes with arbitrary positions. The ITS node positions are feed to a cooperative measurements simulator which also takes the true trajectory from the OXTS high-precision position and attitude system (see [8] for more information about the reference positioning system). Based on the technology parameters setup, the cooperative measurements simulator MATLAB script generates a set of range estimations ($\hat{\rho}_c$) to the nodes that are within the radio coverage for the current vehicle reference position. Along the simulated range measurements, the script also produces their associated measurement covariances ($\hat{R}_c$). Both GNSS measurements and IMU measurements are obtained using real sensor data, captured during a measurement campaign. As described in detail in [8] all sensors measurements are synchronized using the GPS time reference. The data set used for the simulations presented in this work are based on the data obtained in the first testing campaign in Helmond/Eindhoven.

The GNSS/INS/Cooperative positioning algorithm is implemented also in a MATLAB script. It is feed with three time-synchronized data sources:

- GNSS data: pseudoranges ρ_G and pseudorange rates $\dot{\rho}_G$
- INS data: 3 Axis accelerometer $\mathbf{f}_{ib}^b$, Gyroscope $\mathbf{w}_{ib}^b$, Magnetometer $\mathbf{m}_{ib}^b$ + Car odometry v_{odo} (speed data)
- Cooperative measurements: Node measurement ranges ρ_C and its covariances $\mathbf{R}_C$.

In addition, the algorithm has access to:

- GNSS satellite positions for specific timestamps $\hat{\mathbf{r}}_{SAT}^e$
- Cooperative node positions $\hat{\mathbf{r}}_c^e$

All the data sources considered in the simulation are feasible for a real-time positioning device. The prototype developed in [8] was enhanced to support cooperative measurements without rewriting the implemented modules and data structures. Finally, the positioning performance is obtained by computing the performance metrics given in terms of the position and velocity accuracy and precision figures.

Cooperative ranging measurement models

The ranging measurements from cooperative nodes $\hat{\rho}_c$ are generated according to a statistical error model. We focus on nodes that acquire distance estimates from time measurements, namely TOA. These are the schemes that provide higher accuracy in the distance estimate. Models based on a Gaussian error distribution are proven accurate to model ranging errors in multipath environments [10, 11]. This is the case of TOA based estimates for UWB technology such as [11] where ranging errors in multipath scenarios take the form of a Gaussian distribution:

$$\hat{\rho}_c \sim (\mathcal{N}(\mu_c(d), \sigma_c^2(d)), \quad (1)$$

with mean and variance characterized by a second order polynomial depending on the distance d ,

$$\mu_c(d) = \alpha_1 d^2 + \beta_1 d + \gamma_1 \quad (2)$$

$$\sigma_c^2(d) = \alpha_2 d^2 + \beta_2 d + \gamma_2, \quad (3)$$

Fig. 5. GNSS/IMU/Cooperative sensor fusion algorithms validation framework.

Fig. 6. Google Earth 3D representation of the selected urban canyon situation in Eindhoven.

which coefficients depend on the particular scenario. In outdoor scenarios there are fewer works that characterise statistically the measurement error. Works in [13, 14] provide a statistical characterization of the ranging error based on emulation and measurements, respectively for OFDM-based waveforms in outdoor scenarios. We consider [13] since characterization is for longer range than [14]. In [13] the error performance is analysed for LTE based ranging, for a dominant LOS scenario with negligible multipath effect, denoted as quasi-AWGN and a strong multipath scenario, such as the urban channel. For the LOS environment the error is modelled as,

$$\hat{\rho}_c = \rho_c + e \quad (4)$$

where $e \sim \mathcal{N}(\mu, \sigma_e^2)$ follows a Gaussian distribution with mean μ and standard deviation σ_e^2 . For the scenario with strong multipath component we resort to a numerical approach based on the cumulative density function results in the urban channels (see Fig. 5-18 from [13]). That is, the ranging measurements are modelled as random variables with realisations generated by inverse transform sampling applied to the CDF in [[13], Fig.5-18].

Simulation scenarios and performance results

One of the most challenging situations for the positioning system is the urban canyon. GNSS signal is severely affected by multipath, and, based on the dynamic measurement covariances estimations, the positioning algorithm should automatically give more weight to the information coming from the cooperative measurements. Fig. 6 shows an overall 3D render of the selected urban canyon situation in Eindhoven. Green line represents the true trajectory obtained using OXTS positioning reference equipment [15].

The cooperative scenario setup is shown in Fig. 7. A set of 8 simulated LTE base stations anchor nodes were deployed at arbitrary positions within a circle around the densest urban area in the vehicle trajectory. Table 1 shows the measurement model parameters for this setup.

Fig. 7. Cooperative node positions (red boxes) in the urban canyon scenario.

Cooperative node parameters	Value
Distance measurement model	LTE TOA LOS (See Eq. 4)
Maximum range	500 m
Measurement availability within the node range	100%
NLOS model parameters	No multipath
LOS model parameters	Mean error = 34 cm Std deviation = 1.6 m

Table 1. LTE LOS cooperative nodes parameters in the urban canyon.

Cooperative node parameters	Value
Distance measurement model	LTE TOA NLOS (See Eq. 1)
Maximum range	500 m
Measurement availability within the node range	100%
NLOS model parameters	Inverse CDF form LTE multipath model available in ([13], Fig.5-18).

Table 2. LTE NLOS cooperative nodes parameters in the urban canyon.

The cooperative positioning performance is shown in Fig. 8. It is possible to observe that the Tightly Coupled GNSS/INS/Odometry algorithm (TC standalone in the figure legend) has significant positioning error during the trajectory. In this situation, the cooperative version of the TC algorithm (TC cooperative in the figure legend), that uses the cooperative measurements from the nodes in view, significantly improves the positioning performance and matches the true trajectory.

Figure 9 shows the same scenario but reducing the number of LTE anchor nodes from 8 to 4. The cooperative positioning algorithm performance is maintained mainly due to the good geometry of the nodes distribution in addition to the LOS configuration with no multipath in all the available nodes. On the other hand, in Fig. 10 is simulated the same 4-nodes scenario with 3 nodes affected by multipath. The nodes labelled with LTEb have a NLOS configuration described in Table 2 and the node labelled with LTEa is using the LOS configuration of Table 1. The performance of the cooperative algorithm is degraded as the

Fig. 8. Cooperative positioning (8 nodes, no multipath).

Fig. 9. Cooperative positioning (4 nodes, no multipath).

Cooperative node parameters	Value
Distance measurement model	WSN (See Eq. 4)
Maximum range	100 m
Measurement availability within the node range	100%
NLOS model parameters	No multipath
LOS model parameters	Mean error = 34 cm Std deviation = 3 m

Table 3. WSN node simulation parameters for the urban road tunnel scenario.

cooperative measurements are affected by large errors due to the multipath effect. It can be appreciated in the first part of the trajectory. As soon as the LOS node is within the measurement range, the cooperative algorithm is able to correct the trajectory and the positioning performance is recovered. Figure 11 and Fig. 12 show a plot of the distance measurements of a LTE node in LOS and in NLOS conditions, respectively. It is noticeable the degradation of the distance accuracy and precision when the multipath affects the node.

Finally, in a situation where the GNSS signal is denied, the cooperative positioning information should enable the positioning algorithm to keep the performance and avoid the dead reckoning to drift. Figure 13 shows a recreation of such situation, where a complete blockage of GNSS signal was simulated in a segment of the vehicle's trajectory, simulating an urban road tunnel. Red boxes are a set of anchor nodes deployed at arbitrary positions to provide coverage inside the tunnel. Blue line shows the positions obtained with the GNSS receiver standalone. Notice that there is an interruption of the positions in the tunnel entrance, restored in the tunnel exit. The plot shows a straight line between the tunnel entrance and the exit coordinates.

The GNSS/INS tightly coupled sensor fusion algorithm (referred to as TC Standalone in the plot) relies only on dead reckoning during the GNSS blackout, thus, the positioning error grows with time. As described in [8], this phenomena is caused by the low-cost IMU bias instabilities. In contrast, the enhanced version of the algorithm, which supports cooperative positioning information, can use the distance measurements to the nodes located at known positions inside the tunnel. It can be seen (referred to as TC Cooperative in the plot) that the positioning performance delivered by the algorithm almost matches the reference positioning performance (referred to TASS reference in the plot legend).

Table 3 shows the cooperative node simulation parameters for the tunnel simulation. In contrast to the urban canyon scenario, it is feasible to use an indoor positioning technology, such as UWB RTOA, for the nodes deployed inside the tunnel facility. The node range is set to 100 m, which is realistic for a four-lane tunnel. Regarding the ranging performance, the range measurement bias was set to 1 meter and the standard deviation was set to 3 meters, which is consistent with a LOS propagation with moderate timing errors. In Fig. 14 can be seen the simulated node distance measurements during the tunnel trajectory. Depending on the timestamp, the vehicle can measure distances to 3 to 6 cooperative nodes.

Fig. 10. Cooperative positioning in the urban canyon (4 nodes: 3 NLOS and 1 LOS).

Fig. 11. LTE node distance measurements in a LOS condition. **Fig. 12.** LTE node distance measurements in a NLOS condition.

Fig. 13. Cooperative positioning in a GNSS-denied situation (simulated urban road tunnel).

Fig. 14. Node distance measurements inside a simulated urban road tunnel.

Fig. 15. Cooperative positioning in a GNSS-denied situation (simulated urban road tunnel with reduced node range coverage to 50 meters).

Fig. 16. Node distance measurements inside a simulated urban road tunnel with reduced node range coverage to 50 meters.

In order to assess the effect of the reduction of the node range, due to the presence of tunnel walls between the lane directions of due signal propagation impairments, a new experiment was simulated for a maximum node range coverage reduction from 100 meters to 50 meters and an increase of the standard deviation error from 3 meters to 5 meters. Performance results are available in Fig. 15. It can be seen a slight reduction of the positioning accuracy in the tunnel trajectory, but the lane-level accuracy is still obtainable. Figure 16 shows the cooperative distance measurements. In this case, the maximum simultaneous available nodes are reduced from 6 to 3.

PROTOTYPE RESULTS

The cooperative sensor fusion algorithm was also tested with real-life UWB nodes in a field test in the seaside road of Castelldefels (Barcelona, Spain). The seaside road was chosen due to its excellent GNSS coverage which enable the reference positioning system to produce high accuracy results. A urban tunnel (total GNSS blockage) was artificially produced for the GNSS/INS/UWB sensor fusion prototype. In a situation where the GNSS signal is denied, the cooperative positioning information should enable the positioning algorithm to keep the performance and avoid the dead reckoning to drift. Typical situations include cross-roads bridges and urban tunnels. Figure 17 shows a picture of the vehicle setup with the UWB mobile node located on its roof in a tripod. One of the deployed anchor nodes is shown in Fig. 18. Figure 19 shows a detail of the UWB node patch antenna.

The anchor nodes deployment plan is shown in Fig. 20. Six anchor nodes were deployed at known locations, positioned using a hand-held GNSS receiver (SBAS enabled). It is expected a bounded error in the anchor GNSS nodes positions due to the GNSS positioning in the order of 1 meter. The node positioning error was further reduced by adjusting the positions by projecting them to referenced satellite images (OpenStreet maps and Google maps).

Fig. 17. Vehicle setup.

Fig. 18. UWB anchor node setup.

Fig. 19. UWB anchor node detail.

Fig. 20. Cooperative nodes scenario setup.

Fig. 21. Castelldefels seaside road near Barcelona (Spain).

Fig. 22. Test vehicle on the road during the field trial.

Fig. 23. Cooperative positioning results vs. GNSS/INS sensor fusion algorithms.

The vehicle was driven to perform regular circulation at 30 km/h of average speed in the sea-side road. Figures 21 and 22 shows pictures of the road and the vehicle during the test drive, respectively. All sensors included the UWB measured distances were logged using the logging feature of the positioning prototype (see [8] for more details). Different positioning algorithms were tested in post-processing mode inside the same Raspberry PI3 platform prototype using the captured dataset.

The position estimation results are shown in Fig. 23 for the following algorithm variants:

- **Ref. GNSS without tunnel:** This is the reference positioning (considered as the *ground true*) obtained by the on-board standalone GNSS receiver.
- **TC GNSS/INS:** is the tightly-coupled algorithm that uses the pseudoranges and its rates from the GNSS receiver and the inertial measurements from the IMU.
- **TC/GNSS/INS/Coop:** is the enhanced tightly-coupled algorithm that includes the cooperative positioning information from the UWB mobile node, as described in Section .
- **LC GNSS/INS:** is the loosely-coupled algorithm that uses the position and velocity from the GNSS receiver and the inertial measurements from the IMU.

An artificial tunnel (GNSS measurements disabled) was produced in the region limited by the yellow line. In this situation, the algorithms relying only on dead reckoning (LC GNSS/INS and TC GNSS/INS) quickly drift during the curve. One of the main contributing factors was the reduction of the vehicle speed (and its angular rate) during the maneuver, which decreased the gyroscope signal-to-noise ratio. On the contrary, the TC/GNSS/INS/Coop algorithm is able to use the distance measurements from the anchor nodes to the vehicle to correct the dead reckoning positioning and reduce the drift dramatically. The field test performance is clearly aligned with the simulated performance.

CONCLUSIONS

Based on the standalone GNSS/INS/Odometry sensor fusion techniques reported by the authors in [8], the Tightly Coupled GNSS/IMU sensor fusion algorithm was enhanced to use generic cooperative ranging measurements. The proposed cooperative positioning algorithm enjoys technology-agnostic features. Thus, ensuring the current and future application with heterogeneous technologies, such as LTE, UWB and RSS among others. In order to assess the positioning performance, the simulator developed in [8] was also evolved to support a mixture of GNSS and IMU real-life measurements, which were recorded with the positioning prototype during the measurement campaign, and simulated cooperative positioning nodes featuring different technologies. Three different cooperative positioning scenarios were identified:

- Inter-urban scenario: good GNSS signal and good cooperative nodes visibility
- Urban canyon: poor GNSS signal, strong multipath and good cooperative nodes visibility

- Urban road tunnel: GNSS-denied environment, good cooperative nodes visibility

The algorithm performance was evaluated for each scenario and for different cooperative node measurement models and signal propagation conditions. The results show a noticeable improvement in the positioning accuracy, especially in the urban canyon and in the GNSS-denied environment. In simulations, the lane-level positioning accuracy was reached in all the cooperative scenarios. In addition, the cooperative sensor fusion algorithm was also implemented in a prototype and tested with real-life UWB nodes in a field test. A urban tunnel (total GNSS blockage) was artificially produced for the GNSS/INS/UWB sensor fusion prototype. In a situation where the GNSS signal is denied, the cooperative positioning information enabled the positioning algorithm to keep the performance and avoided the dead reckoning to drift. The field test performance was aligned with the simulation results.

ACKNOWLEDGEMENTS

This work was supported in part by the TIMON Project: Enhanced real time services for an optimized multimodal mobility relying on cooperative networks and open data and in part by the European Union's Horizon 2020 Research and Innovation Programme under Grant 636220, the Spanish Ministry of Economy and Competitiveness (project TEC2015-69868-C2-2-R ADVENTURE), the Government of Catalonia (Grant 2017-SGR-1479) and by the EC in the framework of the COST Action CA15104 (IRACON).

REFERENCES

- [1] "Global Positioning System Wide Area Augmentation System (WAAS) Performance Standard GPS WAAS PS v1.0," Tech. Rep., US Department of transportation and Federal Aviation Administration, 2008.
- [2] European Commission Directorate-General for Energy and Transport, "EGNOS Service Definition Document: Open Service EGN-SDD OS V1.0," Tech. Rep., 2009.
- [3] F. Diggelen, *A-GPS: Assisted GPS, GNSS, and SBAS*, Artech House, 2009.
- [4] M. Hernández-Pajares, J. M. Juan, J. Sanz, A. Aragon-Angel, P. Ramos-Bosch, D. Odijk, P. Teunissen, J. Samson, M. Tos-saint, and M. Albertazzi, "Wide-Area RTK: High Precision Positioning on a Continental Scale," *Inside GNSS*, pp. 35–46, March–April 2010.
- [5] J. A. Farrell and M. Barth, *The Global Positioning System & Inertial Navigation*, McGraw–Hill, 1999.
- [6] M. S. Grewal, L. R. Weill, and A. P. Andrews, *Global Positioning Systems, Inertial Navigation, and Integration*, 2nd Ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 2007.
- [7] P. D. Groves, *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*, 2nd Ed., Artech House, Norwood, United States, 2013.
- [8] J. Arribas, A. Moragrega, C. Fernández-Prades, and P. Closas, "Low-cost GNSS/INS/Odometric sensor fusion platform for ground intelligent transportation systems," in *Proceedings of the ION GNSS 2017, Portland, Oregon (USA)*, September 2017.
- [9] "Enhanced real time services for an optimised multimodal mobility relying on cooperative networks and open data (TIMON) project, European Union's Horizon 2020 research and innovation programme under grant agreement No 636220," 2016, <https://timon-project.eu/>.
- [10] N. Alam and A. G. Dempster, "Cooperative positioning for vehicular networks: Facts and future," *IEEE Trans. On Intelligent Transportation Systems*, vol. 14, no. 4, pp. 1708–1717, August 2004.
- [11] H. Wymeersch, J. Lien, and M. Z. Win, "Cooperative localization in wireless networks," *IEEE Trans. On Intelligent Transportation Systems*, vol. 97, no. 2, pp. 427–450, February 2009.
- [12] DecaWave Ltd, "Ready to go RTLS kit designed for DWM1001 evaluation and fast application development," Webpage, accessed 1 Feb. 2018, <https://www.decawave.com/>.

- [13] J.A del Peral-Rosado, *Evaluation of the LTE positioning capabilities in realistic navigation channels*, Ph.D. thesis, Universitat Autònoma de Barcelona (UAB), March 2014.
- [14] E. Staudinger and A. Dammann, "Round-trip delay ranging with OFDM signals - Performance evaluation with outdoor experiments," in *Proceedings of 11th Workshop on Positioning, Navigation and Communication (WPNC)*, Dresden, 2014, pp. 1–6.
- [15] "OXTS RT3003 Inertial and GPS Navigation System," Retrieved: February 1, 2017, <http://www.oxts.com/product/rt3003/>.