ANALYSIS OF THE PERFORMANCE OF AN UWB-BASED COOPERATIVE POSITIONING FOR DIFFERENT CAR PLATOON CONFIGURATIONS

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KEY WORDS: Collaborative positioning, UWB, Extended Kalman filter.

ABSTRACT:

The increasing interest in autonomous vehicles motivates the researches aiming at developing reliable positioning system also in conditions challenging for the Global Navigation Satellite Systems (GNSS), such as in urban canyons, tunnels, under quite dense vegetation. The uso of Ultra Wide-Band (UWB) systems is among the quite well known methods for providing reasonable positioning results without exploiting GNSS. UWB systems are typically used indoors, however their use can be of interest also outdoors, in particular when the need is to ensure good positioning results over a quite small area. This paper investigates the use of UWB systems for positioning in the case of terrestrial vehicles, and, more specifically, it focuses on checking the influence of car platoon configurations on the performance of an UWB cooperative positioning system. In the considered tests, where a high percentage of UWB communications was successful, the obtained results show that the car configuration can have a quite remarkable impact on the positioning performance, doubling the obtained median error.

1. INTRODUCTION

Despite the use of Global Navigation Satellite Systems (GNSS) currently ensures a good user experience in most of the working conditions, there are several challenging environments and conditions in which GNSS cannot be safely and effectively used as a stand alone solution.

The above observation and the increasing interest on autonomous vehicles, and in particular on autonomous driving cars, are motivating the search for different positioning techniques, which could be effectively used for obtaining an accurate ubiquitous positioning system (Yao et al., 2011, Mohammadmoradi et al., 2019, Alam and Dempster, 2013, Shen et al., 2017, Adegoke et al., 2019, Petovello et al., 2010) .

Among the technologies that have already shown a clear potential there surely are Ultra Wide-Band (UWB) ranging, and vision.

Ultra Wide-Band (UWB) positioning systems are usually based on a static infrastructure of UWB transceivers. Vehicles are provided with at least one UWB transceiver, able to communicate with the static infrastructure: ranging measurements between such transceiver and the infrastructure (V2I) is typically obtained by means of two-way time-of-flight (TW-ToF) (Gabela et al., 2019, Sakr et al., 2020). Generally, such range observation is quite accurate, typically leading to quite good positioning performance at relatively short distances. Hence, their use in a cooperative positioning system is quite advantageous in particular when the vehicles are quite close to each other, for instance at road intersections (Amini et al., 2014). Furthermore, the effectiveness of an UWB positioning system is expected to be dependent on the geometric configuration of the UWB network. For instance, all the UWB devices distributed along a line should represent a weak geometric configuration for what concerns the computation of an UWB-based positioning solution.

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When UWB ranging is available from a static UWB infrastructure it is possible to use such ranges in a position fix approach, otherwise, relative positioning may still be considered if at least vehicle-to-vehicle (V2V) ranges are available.

This paper aims at investigating the performance of a car cooperative positioning approach based on UWB measurements. The considered dataset includes:

- GPS/GNSS, for each car, to be used as references,
- V2V ranging, between each couple of cars,
- V2I ranging, with the ten UWB anchors,
- multiple cameras, mounted on one of the vehicles. Two of them in a stereo rig-like configuration.

The static UWB infrastructure and, partially, the other sensors mounted on the vehicles, are visible for instance on Figure 1, and, more precisely, the test area considered in this work is shown in Figure 2 (red box).

Exploiting the information from both UWB ranging and camera information has already been partially investigated in (Masiero et al., 2021, Masiero et al., 2020), where camera was used in order to detect other vehicles and determine their relative position with respect to the camera (and to its vehicle). Vehicle detection was done by means of a deep learning approach (Yolo v3 network (LeCun et al., 2015, Redmon and Farhadi, 2018), trained ad hoc for such specific task).

Instead, this paper focuses just on UWB-based vehicle cooperative positioning, and, in particular, it investigates the influence of vehicle configurations on the obtained positioning performance.

Indeed, positioning performance is influenced by the UWB network geometric configuration (Dabove et al., 2018), and by the

Figure 1. Example 1 of car configuration.

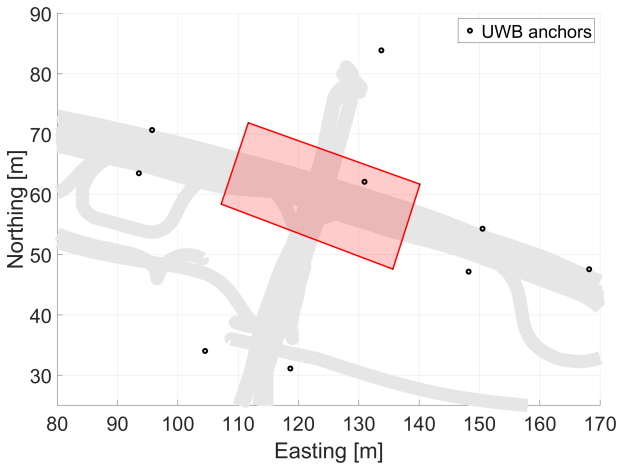

Figure 2. Test area. Red box: main region of interest.

vehicle relative distances (Masiero et al., 2021). Hence, the main goal of the paper is that of analyzing the performance variations due to such factors, and in particular to the car platoon geometric configurations.

Figures 1, 3 and 4 show few examples of car platoon configurations. Among the examples shown in such figures, that of Figure 4 is of particular interest, i.e. determining the system performance in certain critical working conditions such at road intersections, where a correct functioning of the positioning system is mandatory for safety reasons.

Figure 3. Example 2 of car configuration.

Figure 4. Example 3 of car configuration.

2. POSITIONING METHOD

The UWB cooperative positioning method used in this work is grabbed from (Masiero et al., 2021). A short summary of the method is reported below, but the reader is referred to (Masiero et al., 2021) for a more detailed description.

An Extended Kalman Filter (EKF) approach is used to assess the state value $\mathbf{x}_k$ at time t_k, and in particular the vehicle position, based on all the available measurements, in centralized way. $\mathbf{p}^{c_i}(t)$ and $\mathbf{v}^{c_i}(t)$ are the position and velocity of the ith vehicle at time t, and $\mathbf{x}_k$ is the joint state vector at time t_k.

Let n be the number of cooperating vehicles, then $\mathbf{x}_k$ is formed by the state vectors of each of the vehicles $\mathbf{x}_k = \left[\begin{array}{ccc} \mathbf{x}_k^{c_1\top} & \dots & \mathbf{x}_k^{c_n\top} \end{array} \right]^\top$, being $\mathbf{x}_k^{c_i}$ the state part corresponding to the ith car: $\mathbf{x}_k = \left[\begin{array}{c} \mathbf{p}^{c_i}(t_k) \\ \mathbf{v}^{c_i}(t_k) \end{array} \right]$.

A simple first-order dynamic model is used to describe the state evolution of each car in Δt_{k+1} seconds:

$$\mathbf{x}_{k+1}^{c_i} = F_k' \mathbf{x}_k^{c_i} + \omega_k \tag{1}$$

where F_k' is

$$F_k' = \left[\begin{array}{cc} I & \Delta t_k I \\ 0 & I \end{array} \right] \tag{2}$$

ω_k is assumed to be a normally distributed zero-mean white noise process, with covariance matrix Q_k.

Then, the dynamic matrix F_k of the all state vector is block diagonal, where each diagonal block is F_k'.

Differently from (Masiero et al., 2021), this paper considers only V2V UWB ranges (i.e. despite being present, V2I are not exploited), hence the observation vector $\mathbf{z}_k$ can be decomposed in two different types of measurements, GNSS and V2V UWB ones: $\mathbf{z}_k = \left[\begin{array}{cc} \mathbf{z}_k^{GNSS\top} & \mathbf{z}_k^{V2V\top} \end{array} \right]^\top$.

The measurement model is assumed to be $\mathbf{z}_k = h_k(\mathbf{x}_k) + \xi_k$, where the rows in $h_k(\cdot)$ are determined depending on if GNSS or V2V UWB measurements are available, i.e.:

$$h_k^{GNSS,i}(\mathbf{x}_k) = \begin{bmatrix} I & 0 \end{bmatrix} \mathbf{x}_k^{c_i} \tag{3}$$

when a GPS/GNSS measurement is available on car i, or

$$h_k^{V2V,i_1,i_2}(\mathbf{x}_k) = \left| \mathbf{p}_k^{c_{i_1}} - \mathbf{p}_k^{c_{i_2}} \right| \tag{4}$$

when a V2V measurement between two cars, i_1 and i_2, is available. In the above equation, $\mathbf{p}^j$ stands for the position of anchor j, whereas $\mathbf{p}_k^{c_{i_1}}$ and $\mathbf{p}_k^{c_{i_2}}$ are the positions of the two cars when the range measurement is taken.

Then, the linearized observation matrix H_k can be separated in two parts: one H_k^{GNSS} referred to GNSS and one H_k^{UWB} to V2V UWB measurements:

$$H_k^{GNSS} = \left[\begin{array}{cc|c|c|cc} I & 0 & \dots & \dots & 0 & 0 \\ 0 & 0 & I \;\; 0 & \dots & \vdots & \vdots \\ \vdots & \vdots & 0 \;\; 0 & \dots & 0 & 0 \\ 0 & 0 & \dots & \dots & I & 0 \end{array}\right] \tag{5}$$

and

$$H_k^{UWB} = \left[\begin{array}{cc|c|c} \mathbf{h}_k^{c_1,c_2} & \mathbf{h}_k^{c_2,c_1} & 0 & 0 \\ \mathbf{h}_k^{c_1,c_3} & 0 & \ddots & 0 \\ & \vdots & & \vdots \\ 0 & 0 & \dots & \mathbf{h}_k^{c_n,c_{n-1}} \end{array}\right] \tag{6}$$

where $\mathbf{h}_k^{c_{i_1},c_{i_2}}$ is computed by linearizing the corresponding terms in h_k^{V2V}.

Since UWB measurements are not acquired in the same time instant, such time difference should is taken into account in the positioning algorithm: assuming a constant velocity during such short time intervals, the vehicle position is compensated taking into account of such a short time difference (more details can be found in (Masiero et al., 2021)).

3. RESULTS AND DISCUSSION

The presented UWB cooperative positioning approach is tested on a 4-vehicle case study (namely, the four vehicles will be named hereafter: The Ohio State University GPSVan, Acura, Honda, Toyota), where V2V UWB communications were available between all the vehicles, along with GNSS reference trajectories. V2I UWB ranging and cameras were available on one of the vehicles, but not exploited in this paper. A more detailed description of the experimental scenario can be found in (Retscher et al., 2020, Masiero et al., 2021). In particular, the dataset used here was collected on the same site of the dataset considered in (Masiero et al., 2021). Figure 2 shows the area of main interest in the test, where an UWB static infrastructure was also installed (but not used here).

In order to reduce the risks of weak solutions at least two cars should be provided of good positioning measurements, either provided by GNSS or by the V2I UWB network (Masiero et al., 2021). In practice, here two vehicles are assumed to be provided with good positioning measurements (GNSS), whereas the positions of the other two are assessed only by means of the V2V UWB measurements.

Since the main goal of this work is that of investigating the influence of different vehicle geometric configurations, four cases are distinguished:

- Case study 1: vehicles are all moving along the same road and in the same direction (the initial configuration is shown in Figure 5, whereas the results in Figure 6). Case 1a) and 1b) compares the results obtained by varying the choice of the two vehicles provided with GNSS measurements, i.e. 1a) GPSVan and Honda, 1b) GPSVan and Acura.
- Case study 2: two vehicles are moving along the same road but in opposite directions, then one turns left. The other two vehicles (Honda and Toyota) are mostly static, and provided with GNSS measurements (Figure 7(a)).
- Case study 3: three vehicles moving along the same road, two of them (GPSVan and Toyota, with the latter provided with GNSS measurements) in the same direction, whereas the third (Acura) in the opposite one. The last vehicle was mostly static during the analyzed part of the dataset, and provided with GNSS measurements (Figure 8(a)).
- Case study 4: all the four vehicles at the beginning are moving towards the same road intersection, from different directions. In case 4a) GPSVan and Toyota are provided with GNSS measurements, whereas in 4b) GNSS is available on Acura and Honda (the initial configuration is shown in Figure 9, whereas the results in Figure 10).

In the initial vehicle configurations, shown in Figure 5, 7(a), 8(a) and 9, the arrows indicate the vehicle moving directions, and their length is proportional to the initial vehicle speed.

The graphical results in the four cases are shown in Figure 6(a) (for case 1a) and (b) (for case 1b), in Figure 7, Figure 8 and Figure 10(a) and (b) (for case 4a and 4b). In these figures, reference trajectories are shown as solid lines, whereas those of the two not provided with GNSS measurements (hence estimated only by means of V2V UWB cooperative positioning) are shown as circular marks.

The numerical results (median and median absolute deviation of the 2D positioning error for the two cars not provided with GNSS measurements) for all the considered cases are reported in Table 1.

Some observations are now in order:

	median [cm]	MAD [cm]
Case 1a	59	8
Case 1b	62	5
Case 2	25	15
Case 3	86	13
Case 4a	59	23
Case 4b	105	51

Table 1. 2D positioning results. LiDAR refers only to those time instants when the Pedestrian were detectable (e.g. not occluded).

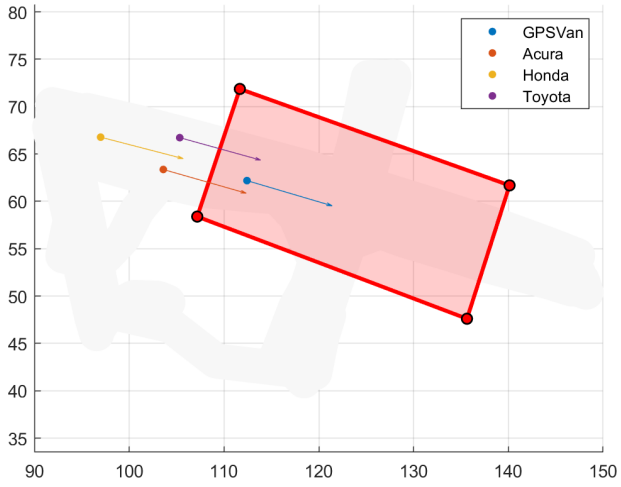

Figure 5. Case study 1: vehicle starting configuration.

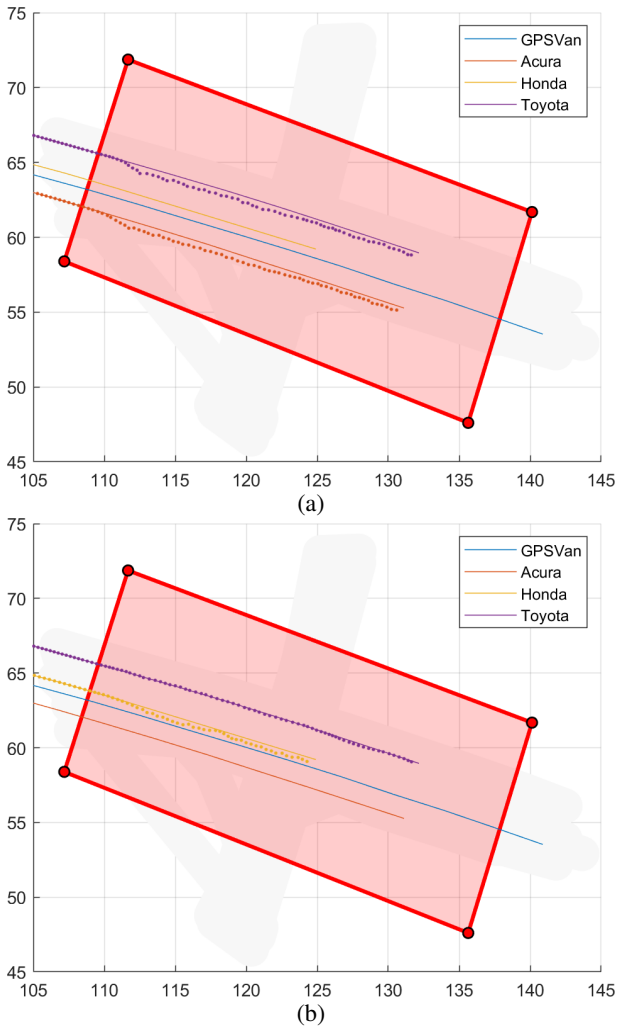

Figure 6. Reference (solid lines) and estimated (circular marks) vehicle tracks in case study 1a (a), and 1b (b).

- First, in accordance with (Masiero et al., 2021), a look to the numerical results in Table 1 show that the use of V2V ranges instead of V2I ones (which are those more typically used in UWB positioning) seems to lead to quite similar results, as long as the positions of certain cars is well known (GNSS measurements are used on two vehicles per time in these experiments).

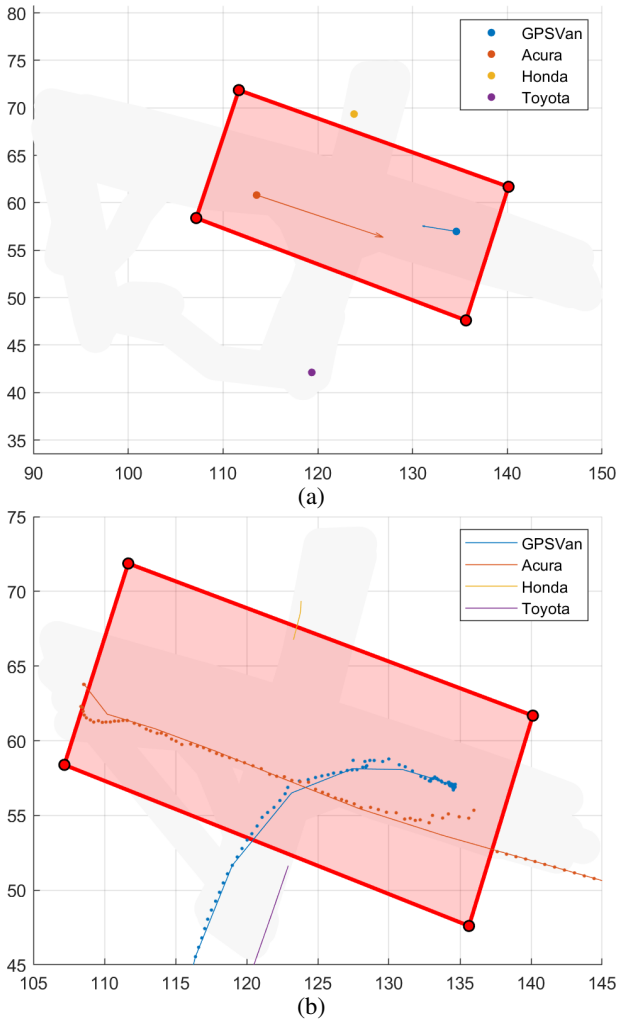

Figure 7. Case study 2: (a) vehicle starting configuration, (b) vehicle tracks.

- Despite the different configurations of the cars with well known positions in case 1a and 1b, the obtained results are similar. Case 2b was supposed to be characterized by a weaker configuration (e.g. the two vehicles with GNSS were closer to each other), however the numerical results show only a very small increase in the median positioning error with respect to case 1a: probably the use of straight trajectories all in the same direction for all the cars helped the positioning algorithm.

- Best results have been obtained in case 2, where the two vehicles with good position information (Honda and Toyota) were mostly static while the others were moving. Despite being static, the main reason for providing the best results should be from a geometric point of view the cars, and in particular the positions of Honda and Toyota with respect to the others, formed a quite robust network during most of the test, with a decreased performance when Acura was at longer distances from the other cars.

- In case 3 the positioning results are quite intermediate, with a degradation for Acura during the last part of the test, probably due to the increased distance with respect to

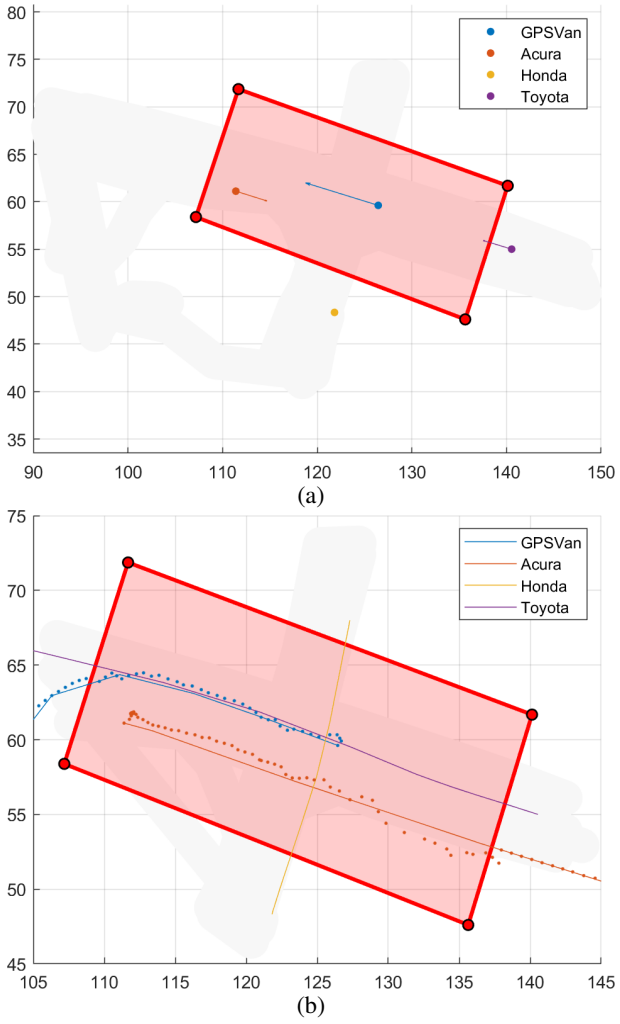

Figure 8. Case study 3: (a) vehicle starting configuration, (b) vehicle tracks.

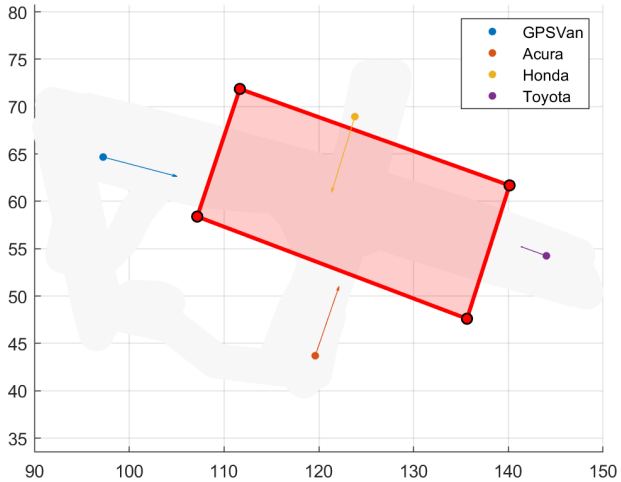

Figure 9. Case study 4: vehicle starting configuration.

GPSVan and Toyota (and hence less available ranges, and with a higher probability of being affected by the presence of objects in the scene).

- A comparison of the results obtained in cases 4a and 4b shows the quite different performance that can be obtained

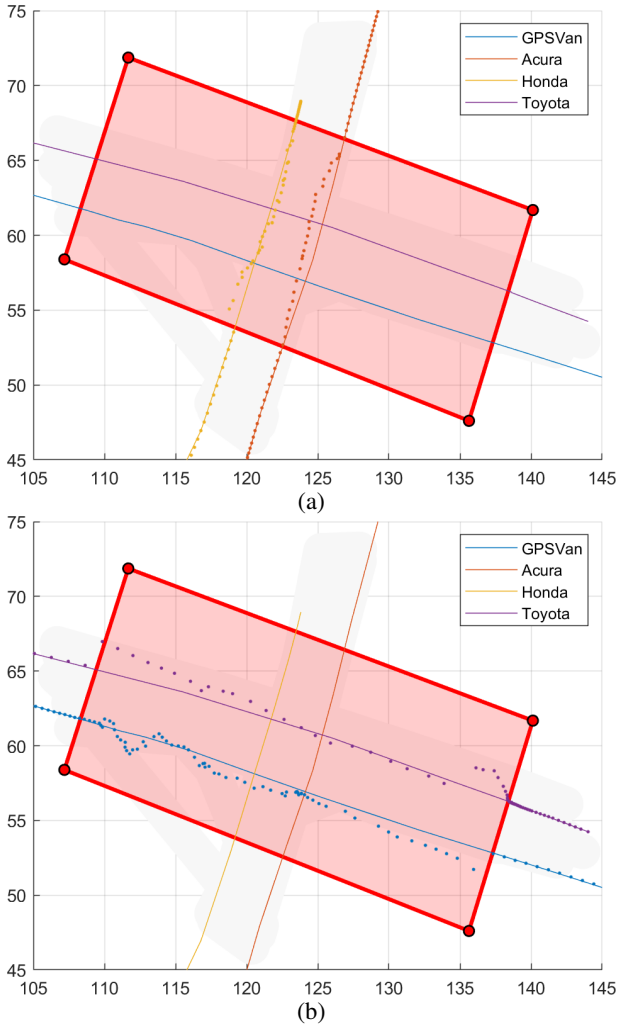

Figure 10. Reference (solid lines) and estimated (circular marks) vehicle tracks in case study 4a (a), and 4b (b).

depending on which of the cars are provided with reliable position measurements. In these case study all the vehicles are moving and passing through the same road intersection. Given the higher speed of Acura and Honda, they reached the intersection before the other cars, and they went straight, moving away from the intersection. In case 4a, GPSVan and Toyota ensured V2V by a position quite close to the road intersection and from two quite different locations, ensuring an overall quite reasonable positioning performance. Instead, in the first part of case 4b Acura and Honda were close to the center of the intersection, hence, even if being both provided with GNSS measurements, such information is not well exploited in this quite weak geometric configuration. After moving away from the intersection, the geometric configuration of Acura and Honda should be much more useful for easing the determination of the other two positions, however, since they moved away from the intersection at higher speed than the other two cars, the increased distances have probably reduced the number (and the quality, due to other objects) of available V2V measurements.

- It is also worth to notice that, despite not being considered here, obstructions due to other objects in the scene may have had an impact on the obtained results. Nevertheless,

since most of the considered area is in correspondence of the intersection between two roads, the impact on the system performance due to obstructions by other objects should be quite minor in the results shown here.

To conclude, given the obtained results, it is quite apparent the influence of the geometric car configuration on the obtained results, in particular in terms of the robustness of their geometric configuration (and of the positions of the nodes with strong position information with respect to the other vehicles). The distance between the vehicles may also have had a certain influence on the performance, in particular due to the reduction of the successful UWB measurements while increasing the range value (but also due to the presence of obstacles in the scene).

4. CONCLUSIONS

This work analyzed the performance of a cooperative positioning approach based on V2V UWB measurements, and strong position information on certain of the vehicles: in accordance with the results previously obtained in (Masiero et al., 2021), GNSS measurements from two vehicles were used in all the simulations in order to reduce the chances of too weak solutions. The obtained results showed that the use of V2V ranges can lead to results similar to V2I ones if the vehicle configuration is quite robust and the vehicle distances are sufficiently short to ensure good UWB connections between them. Nevertheless, the positioning performance was quite different depending on the considered configuration, showing a remarkable impact of weak car configurations, in particular for what concerns the relative positions of the cars provided with strong position information with respect to the others, and on inter-vehicle distances (being lower the UWB successful measurement rate at larger distances, and being measurements more probably affected by the other objects in the scene for larger ranges).

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