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A Novel GNSS based V2V Cooperative Localization to Exclude Multipath Effect using Consistency Checks

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***Abstract*—Global Navigation Satellite System (GNSS) is essential for autonomous driving by providing absolute positioning solutions. However, the performance of GNSS measurement is significantly degraded in urban areas, due to the severe multipath and non-line-of-sight (NLOS) effects. To ensure the operation safety of autonomous driving applications, the GNSS localization performance is required to improve. In this study, a novel vehicle-to-vehicle (V2V) based cooperative localization algorithm with double-layers of consistency check (CC) is developed. GNSS pseudorange measurements of the ego-vehicle and surrounding vehicles conduct the first-layer of CC independently to exclude the multipath-biased measurement and obtaining their absolute positions. Then, the survived GNSS measurement and the absolute positions of each vehicles are shared in between, and further applied with double difference (DD) technique to obtain an accurate relative position between the surrounding vehicles. The second-layer CC is conducted during the GNSS DD-based relative positioning, to exclude the multipath and NLOS effects more comprehensively. Finally, the absolute and relative positions of surrounding vehicles are cooperated to optimize the final position of all participating vehicles. By the both simulation and real experimental results, the proposed algorithm is able to mitigate the multipath effect and significantly improve the accuracy of GNSS localization solutions to fulfill the safety requirements for autonomous driving.**

Keywords—GNSS; multipath; NLOS; V2V; cooperative localization; autonomous driving; urban; double difference

I. Introduction

Autonomous driving technology is rapidly developing in recent years, aiming to make contributions on traffic safety. The autonomous driving system always have all-round sensing and detecting while human-drivers have blind zone during their driving. The localization accuracy is highly affecting the performance of autonomous driving. The common approach for localization is employing the global navigation satellite system (GNSS) receiver to obtain the position of vehicle. To improve the update rate and accuracy of positioning solutions, the inertial navigation system (INS) is always integrated with GNSS [1]. Due to the development of computing capability, the computer vision and LiDAR are employed for more precious vehicular positioning such as the simultaneously localization and mapping (SLAM) technique [2]. However, unlike other sensors measuring the *relative* position, the GNSS directly provides the *absolute* position without accumulated error. Therefore, GNSS solution is still the key technology to provide the positioning service for autonomous driving [3].

With the development of communication technology, the sharing of the information between vehicles can be realized, which is well-known as vehicle-to-vehicle technique (V2V) communication. By exchanging the information, the sensor measurements from surrounding vehicles can be cooperated to aid the localization of all the participating vehicles [4, 5]. The V2V based cooperative localization can be categorized into transponder-based approach (using RSSI or TDOA), GNSS-based approach and multiple integrated approach [6-8]. A comprehensive review of V2V based cooperative positioning can be found at [9]. While the transponder-based approach can be improved with angel of arrival (AOA) measurement when the time is not synchronized [10], this approach still has the light-of-sight (LOS) requirements. On the contrary, the cooperative localization by sharing of GNSS pseudorange measurements is still feasible when direct communication between vehicles are obstructed [9]. Hence, the GNSS based V2V cooperative localization has great potential and able to cope with complex situations as the real environment for autonomous driving.

GNSS localization accuracy is influenced by several factors, including satellite orbit/clock bias, atmospheric delays, receiver thermal noise and the multipath and non-line-of-sight (NLOS) effects [11]. By employing differential GPS (DGPS) correction, the systematic errors can be corrected from the reference station measurement [12]. Since V2V communication enables exchanging the GNSS raw measurement of the surrounding vehicles, double difference (DD) technique can be applied to eliminate both systematic errors and receiver clock bias [13]. Different cooperative localization approaches are also being developed to optimize the localization accuracy by available shared measurements, such as weighted cooperation [8], least square approach [14] and hypothesis based probability density filter [15]. Moreover, extra constraints from prior knowledge [16], vehicular motion model [17] or map matching [18] is employed within the cooperative localization to enhance the positioning accuracy. However, unlike other positioning error source, the multipath effect and NLOS reception are unable to be corrected by differential techniques [19]. In the other words, it is one of the bottleneck for autonomous driving realization. In urban canyons, the signal transmission of GNSS satellite can be reflected by the building surface, suffering an extra traveling distance [20]. The multipath and NLOS effects are further introducing GNSS positioning error, which can be severe in dense urban areas such as Hong Kong, Shanghai and Beijing. The NLOS error can even exceed 100 meters when operating in urban area and the differential technique can even increase the error [21]. One of the feasible solution is to identify and exclude the multipath and/or NLOS affected signals. Consistency check (CC) of the GNSS pseudorange measurements is recently proposed [22]. In CC, the pseudorange residual can be calculated representing the consistency between the range measurements from different satellites. Since the multi-GNSS is risen with GPS, GLONASS, Galileo and BeiDou, the amount of available satellite is high even in dense urban areas. Therefore, it will not cause the lack of satellite for positioning by excluding the multipath affected signals. The evaluation of CC using GPS, GLONASS and BeiDou measurements in the automobile road test in urbanized areas is given [23]. However, the research indicates the insufficiency of positioning accuracy under deep urban canyon such as Tokyo.

In this study, the objective is to use CC technique to exclude the multipath and/or NLOS effects and apply V2V cooperative localization, achieving more accuracy localization solution for autonomous driving. Firstly, after obtaining the raw GNSS measurements, the first-layer CC is designed to exclude the biased measurement. The inconsistent measurement will be excluded one by one, until the pseudorange residues less than the threshold determined by chi-square test. Then, the survived (multipath excluded) measurements are applied with least square positioning algorithm to obtain the absolute positioning solution for each vehicle. With the help of V2V, DD technique is further used to calculate the relative positions between participating vehicles. Here, the second-layer CC is also designed to exclude the biased measurements. Finally, a novel V2V cooperative localization is developed combining all available information to optimize the absolute position of each vehicle. According to the simulation and experiment result, the proposed novel cooperative localization algorithm can significantly improve the localization accuracy in urban area. The accuracy of positioning result is about 10 meters of positioning error, which roughly fulfills the safety requirement of autonomous driving.

The paper is organized as following: The conventional least square positioning and double difference technique are introduced in section II. The system architecture and detail implementation of the proposed GNSS based cooperative localization algorithm with double-layers consistency check is introduced in section III. The simulation and experiment results are shown in section IV. Finally, the conclusion is drawn in section V.

II. Conventional Positioning Algorithm

To determine the positioning solution using GNSS measurements, the least square (LS) positioning algorithm and the double difference (DD) technique in RTK are commonly employed, obtaining the absolute and relative positioning solution respectively.

A. Least Square Positioning Algorithm

GNSS receiver measures the signal transporting time from the satellite, and further convert into the range in between, namely the pseudorange. By receiving at least 4 satellite measurements, the 3-dimensional (3D) position of the vehicle is able to be determined with all the satellite positions and the corresponding pseudorange. The iterative LS is shown as following:

$$\Delta\mathbf{x} = (\mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{T}}\Delta\boldsymbol{\rho} \tag{1}$$

$\Delta\mathbf{x}$ denotes the state vector, consisting of the difference between prediction and estimation. $\mathbf{H}$ denotes the measurement matrix, consisting of the unit light-of-sight (LOS) vector between the satellites and receiver. $\Delta\boldsymbol{\rho}$ is the vector of pseudorange difference between measurements and predictions. By assuming an initial prediction of position, the position estimation can be calculated by a few iteration.

To ensure enough satellite available after exclusion by CC, the multi-GNSS measurements are used. In this study, the proposed algorithm is evaluated and verified within Hong Kong, where the visibilities of GPS and BeiDou satellite outperforming other combinations of two GNSS constellations (restriction of the low-cost GNSS receiver we used). Since the GPS system time is not synchronized with that of BeiDou, the system clock bias in-between is required to be estimated during the LS estimation. Thus, the state vector including system clock bias and the pseudorange difference vector are shown as following:

$$\Delta\mathbf{x} = \begin{pmatrix} \Delta\mathbf{r} \\ \delta\rho_{rec} \\ \delta\rho^{BDs} \end{pmatrix}, \qquad \Delta\boldsymbol{\rho} = \begin{pmatrix} \Delta\rho^1 \\ \Delta\rho^2 \\ \vdots \\ \Delta\rho^n \end{pmatrix} \tag{2}$$

$\Delta\mathbf{r}$ denotes the difference between prediction and estimation of receiver position, $\delta\rho_{rec}$ denotes the receiver clock offset from GPS system time and $\delta\rho^{BDs}$ is the system clock offset between GPS and BeiDou. $\Delta\rho^n$ denotes the pseudorange difference between measurement and prediction for the n^{th} satellite. Since the conventional LS positioning is based on GPS system time, the BeiDou system clock bias is only used for BeiDou satellite's measurement correction. The measurement matrix $\mathbf{H}$ is given as following:

$$\mathbf{H} = \begin{pmatrix} u_x^1 & u_y^1 & u_z^1 & 1 & \delta^1 \\ u_x^2 & u_y^2 & u_z^2 & 1 & \delta^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ u_x^n & u_y^n & u_z^n & 1 & \delta^n \end{pmatrix} \tag{3}$$

(u_x^n, u_y^n, u_z^n) denotes the unit LOS vector from the receiver to the n^{th} satellite. The δ^n equals to 1 for the n^{th} satellite belongs to BeiDou system and zero for the GPS. By applying this LS positioning, the measurement error due to different GNSS clock bias can be corrected, achieving more accurate positioning solutions.

B. Positioning using Double Difference Measurements

The widely used real time kinematic (RTK) is to employ the GNSS raw measurement from a reference station to improve the localization accuracy of a remote user. By knowing the true location of the reference station, the pseudorange measurements of the user device and reference station are able to conduct the differencing and eliminating the common delays. By extending the idea of RTK, the double difference (DD) technique is also used in the proposed cooperative positioning. Another user device will act as reference station to conduct DD to obtain accurate relative position between two receivers. For the GNSS receiver a, the pseudorange of n^{th} satellite $\tilde{\rho}_a^n$ can be described as following:

$$\tilde{\rho}_a^n = \rho_a^n + \delta\rho_a + \delta\rho^n + \varepsilon_a^n \tag{4}$$

where ρ_a^n is the true range between the receiver a and the n^{th} satellite, $\delta\rho_a$ denotes the receiver clock offset. $\delta\rho^n$ denotes the common bias for the n^{th} satellite, including atmospheric delay and satellite orbit/clock bias. ε_a^n is uncommon error between the two receivers and two satellite measurements, such as the multipath and NLOS delays. As shown in Fig. 1, the single difference of the pseudorange from the same satellite n of both receivers a and b can be derived as following:

$$S_{ab}^n = \vec{e}^n \cdot \Delta\vec{\mathbf{r}}_{ab} + (\delta\rho_a - \delta\rho_b) + (\varepsilon_a^n - \varepsilon_b^n) \tag{5}$$

$\vec{e}^n$ is the unit LOS vector for the satellite n, and $\Delta\vec{\mathbf{r}}_{ab}$ denotes the vector of relative position between receivers a and b. Since the pseudorange is much larger than the relative distance between receivers, the $\vec{e}^n$ can be assumed as the same for both receivers and the pseudoranges are parallel. Therefore, the difference of pseudoranges between receivers a and b can be decomposed by the LOS vector as $\vec{e}^n \cdot \Delta\vec{\mathbf{r}}_{ab}$. By the single difference operation, the common bias of satellite n, $\delta\rho^n$, can be eliminated.

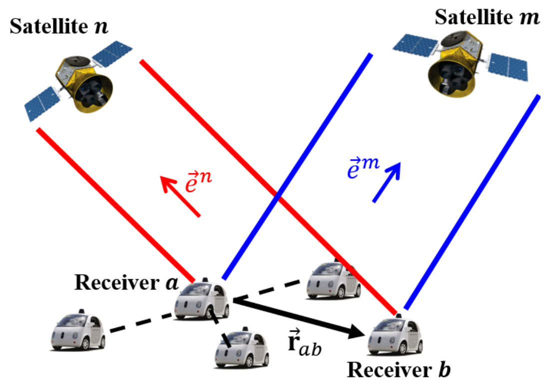

Fig. 1. The illustration of double difference of pseudorange measurements between two receivers a and b.

The difference of single difference result for both satellite n and m can be obtained as following:

$$D_{ab}^{nm} = (\vec{e}^n - \vec{e}^m) \cdot \Delta\vec{\mathbf{r}}_{ab} + [(\varepsilon_a^n - \varepsilon_b^n) - (\varepsilon_a^m - \varepsilon_b^m)] \tag{6}$$

The receiver clock bias of a and b can be eliminated by the double difference operation, only remaining the uncommon errors in between. Similar to the LS using pseudorange measurements, the DD measurements between a reference satellite (usually the highest elevation satellite) and other satellites are able to be integrated and obtain the relative position by LS as following:

$$\Delta\vec{\mathbf{r}}_{ab} = (\mathbf{E}^{\mathrm{T}}\mathbf{E})^{-1}\mathbf{E}^{\mathrm{T}}\mathbf{D}_{ab} \tag{7}$$

where $\mathbf{E}$ is the vector constructed by the difference of the unit LOS vectors between reference satellite and other satellites, and $\mathbf{D}_{ab}$ is the vector of DD measurements between reference and other satellites for receivers a and b. By applying the LS, the relative distance without the biased from systematic error can be calculated. However, the uncommon error cannot be cancelled by DD. Moreover, the DD may even deteriorate the multipath effect in urban, resulting an enormous positioning error. Hence, the multipath error is required to be excluded before applying DD, ensuring the positioning accuracy.

III. Cooperative Localization with Double Layer Consistency Checks

By applying the LS using pseudorange measurements and DD measurements, the relative and absolute positioning solutions can be obtained, respectively. We are able to cooperate both absolute and relative positions to optimize and improve the localization accuracy of the participating vehicles. However, unlike open-sky areas, the GNSS receivers suffer severe multipath and NLOS effects in urban areas, resulting enormous error on both relative and absolute positions. As mentioned earlier, multipath effect is unable to be solved by differencing the measurements. To exclude the multipath effects, a feasible solution is to apply consistency check (CC) on both pseudorange and DD measurements before the LS positioning.

In this study, a GNSS based cooperative localization using double-layer of CC is proposed. The architecture is shown as Fig. 2. In each vehicle, the raw measurements from GNSS receiver is applied with LS positioning that conducted with first-layer consistency check (1st CC), obtaining the absolute position and the associated pseudorange residuals. Besides, the survived measurements from 1st CC is cooperating with other vehicle's survived measurements by DD. A second-layer consistency check (2nd CC) is to exclude the inconsistent DD measurements, obtaining the accurate relative position between two vehicles. By cooperating the absolute and relative positions, the optimized position of each vehicle can be obtained using the proposed weighed cooperative localization algorithm (WCL).

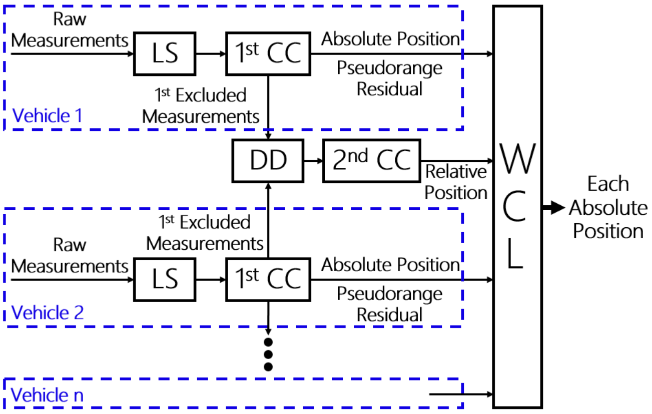

Fig. 2. The architecture of the proposed cooperative localization algorithm.

A. First Layer CC with LS Positioning using Pseudorange Measurements

The 1st CC is developed to observe the consistency between all pseudorange measurements receiver by the GNSS receiver of a specific vehicle. The consistency of measurements can be evaluated by the pseudorange residual $\hat{\boldsymbol{\varepsilon}}_{LS}$ as shown in the following:

$$\hat{\boldsymbol{\varepsilon}}_{LS} = \Delta\boldsymbol{\rho} - \mathbf{H} \cdot \Delta\,\mathbf{x} \tag{8}$$

It is further normalized with the sum of square error SSE_{LS} to evaluate the consistency as following:

$$SSE_{LS} = \hat{\boldsymbol{\varepsilon}}_{LS}{}^{\mathrm{T}} \cdot \hat{\boldsymbol{\varepsilon}}_{LS} \tag{9}$$

A large SSE_{LS} indicates the pseudorange measurements are not consistent, implying some of the measurement is possibly affected by the multipath or NLOS effects. Therefore, we exclude the measurement one by one and repeat the SSE_{LS} evaluation. The measurement set with lowest SSE_{LS} denotes the most consistent subset of measurements, which excluding the inconsistent measurement (probability multipath-affected one). By repeating the consistency check and exclusion, all the inconsistent measurements can be excluded continuously. Until the SSE_{LS} below a threshold determined by chi-square test with 99.999% the probability of false alarm [24]. The detail of the CC algorithm can be found at [23]. The survived measurements are then applied with LS positioning to estimate the absolute position of the vehicle.

B. Second Layer CC with LS Positioning using DD Measurements

The survived measurements after the 1st CC of each vehicle are then cooperated and conducted the DD. To guarantee the DD measurements do not contain multipath effects, 2nd CC is developed to evaluate the consistency of DD measurements of the surrounding vehicles.

Using the LS approach, the pseudorange residual of DD and its corresponding sum of the square error can be illustrated as following:

$$\hat{\boldsymbol{\varepsilon}}_{DD} = \mathbf{D} - \mathbf{E} \cdot \Delta\vec{\mathbf{r}} \tag{10}$$

$$SSE_{DD} = \hat{\boldsymbol{\varepsilon}}_{DD}{}^{\mathrm{T}} \cdot \hat{\boldsymbol{\varepsilon}}_{DD} \tag{11}$$

Similar to the 1st CC, the DD measurement of each satellite is excluded and conducted with 2nd CC one by one. Finally, the most consistent set of DD measurements is selected. Again, the exclusion stops until it is bellowing a threshold based on the chi-square test that employed to guarantee the measurements within an acceptable consistency. After the 2nd CC, the survived DD measurements are further applied into LS, obtaining an accurate relative position between the two vehicles.

C. Weighted Cooperative Localization

The absolute position of each vehicle and the relative position between two vehicles are further applied with the proposed weighted cooperative localization algorithm (WCL), optimizing the position of all the participating vehicles. By selecting the vehicle a from the total number of i vehicles as reference, the position of the reference vehicle and surrounding vehicles can be calculated based on the absolute position of reference from 1st CC and the relative position between reference and surrounding vehicles from 2nd CC as following:

$$\mathbf{v}_{a\in i} = \begin{pmatrix} \mathbf{r_a} + \Delta\vec{\mathbf{r}}_{\mathbf{a1}} \\ \mathbf{r_a} + \Delta\vec{\mathbf{r}}_{\mathbf{a2}} \\ \vdots \\ \mathbf{r_a} + \Delta\vec{\mathbf{r}}_{\mathbf{ai}} \end{pmatrix} \tag{12}$$

where $\mathbf{v}_{a\in i}$ denotes the position matrix for all the vehicles calculated based on vehicle a. $\mathbf{r_a}$ is the absolute positioning of the reference vehicle a and $\Delta\vec{\mathbf{r}}_{\mathbf{ai}}$ is the relative position vector between reference vehicle a and the i^{th} surrounding vehicle. To evaluate the accuracy of $\mathbf{v}_{a\in i}$, a corresponding test statistic TS_a is designed based on consistency of measurement as following:

$$TS_a = \sqrt{\frac{SSE_{LS,a}}{nSat_a}} \tag{13}$$

$SSE_{LS,a}$ is the sum of the square error of LS pseudorange residual as shown in (9) and $nSat_a$ denotes the number of the survived measurements of the reference vehicle a after the 1st CC. As shown in (13), TS_a indicates the mean of the pseudorange residual per measurement. Thus, the lower value of TS_a, the more accurate absolute positioning result is obtained. By selecting each available vehicle as reference, the corresponding all vehicles position matrix and test statistic can be calculated accordingly. Finally, each position matrix estimated using different reference vehicle can be combined with a weighting basing on test statistic as below:

$$\mathbf{V} = \sum_{a=1}^{i} w_a \cdot \mathbf{v_a} \quad (14)$$

$$w_a = \frac{1/TS_a}{\sum_{a=1}^{i} 1/TS_a} \quad (15)$$

V is the optimized position matrix of all vehicles, w_a is a normalized weighting of the vehicle positions estimated based on using vehicle a as reference. By this approach, the absolute positioning solution of each vehicle can be refined and optimized.

IV. Results and Discussions

A. Simulation

The ray-tracing simulation is implemented based on the 3D building model and the predicted satellite position by the broadcast ephemeris [25]. By selecting a location, the signal transmission paths can be traced back from the location to the position of satellite. Assuming the rule of perfect reflection, the multipath and/or NLOS affected pseudorange can be simulated using the 3D building models. The same simulation tool is used to generate a GPS positioning error map of an urban area [26]. In addition, the atmospheric delay and the random noise based on C/N_0 and elevation [27] are added into the measurement, aiming to simulate realistic pseudorange measurements. The selected location of the simulation scenario is Kowloon, Hong Kong. The corresponding 3D building model is manually constructed based on the models of Google Earth. Five locations are selected to simulate the multipath-affected pseudoranges. Their corresponding positioning error estimated by conventional LS is shown as Fig. 3. The measurements from the simulation can be categorized as the case of 4 vehicles with multipath-fee measurements and 1 vehicle with multipath/NLOS affected measurements. Then, the simulated measurements are applied into the proposed double-layer CC based WCL.

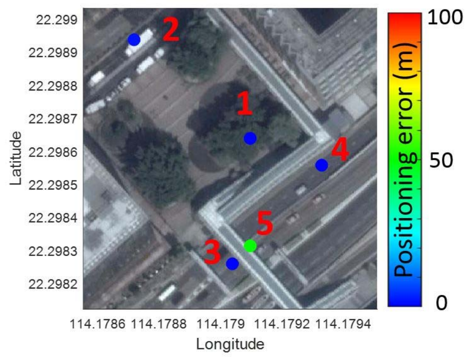

Fig. 3. The selected vehicle locations to generate the simulated pseudorange measurements. The color denotes the corresponding positioning error estimated by LS using the simulated pseudorange measurements. In this case, only the vehicle 5 uses the multipath-affected pseudorange.

By applying the 1st CC and LS, the result is shown as Table I. In the simulated measurements of vehicle 5, the PRN 6, 51 and 91 (bold font in Table I) measurements contained multipath delay, which can be correctly excluded by the 1st CC and resulting a SSE_{LS} lower than the threshold. Since all measurements are added with random noises, the 1st CC will also exclude the inconsistent measurements with high noise, guaranteeing the consistency of measurements. After that, the 2nd CC is further excluded the DD measurement of PRN 5, which is also containing high noise, between vehicles 2 and 5. Therefore, 2nd CC is dealing with inconsistent DD measurement.

TABLE I. 1st CC Result using Vehicle 5 Measurements Simulated and Depicted in Fig.3.

Excluded Satellites	nSat	SSE_{LS}	Threshold
-	25	95902.91	60.70
91, 12, 89, 37, 93, 98, **51**, **6**, 99, 2	15	36.95	45.08

The survived DD measurements are applied into LS to obtain the relative position between the reference vehicle and other vehicles. The error of the estimated relative positions are shown in Fig. 4 and Table II. By applying the 1st CC, the relative positioning error (calculated by differencing two absolute positions estimated by LS independently) can be significantly reduced comparing with the conventional LS. DD can further eliminate the systematic error during calculation of the relative distance. The proposed approach (CC2DD in Fig. 4) achieves the most accurate relative position with a performance that less than 1 meter of mean error.

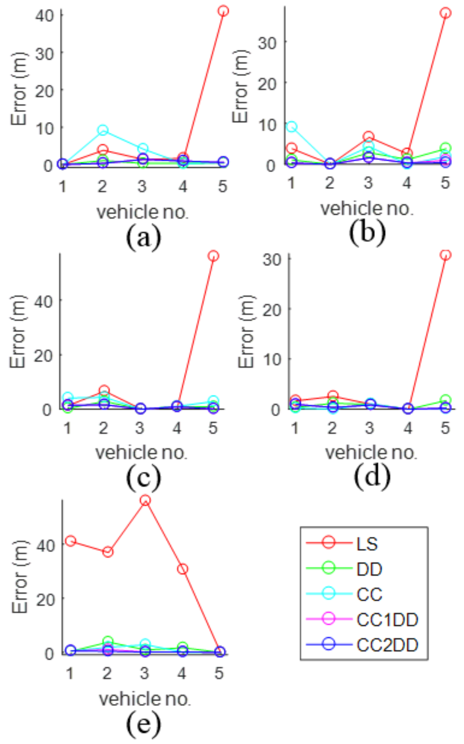

Fig. 4. The error of the estimated relative distance between reference vehicle and surrounding vehicles, the reference is selected as (a) vehicle 1; (b) vehicle 2; (c) vehicle 3; (d) vehicle 4 and (e) vehicle 5. In the legend, LS is the conventional least square method, DD is the conventional double difference, CC is calculating the relative position by two absolute positions passed the 1st CC, CC1DD is the result of using the survided 1st CC measurements into DD and performing LS and CC2DD is the proposed double layer CC method.

TABLE II. THE RELATIVE DISTANCE MEAN ERROR (IN THE UNIT OF METER)

LS	CC	DD	CC1DD	CC2DD
14.51	1.93	1.09	0.59	0.54

The absolute positions and relative positions based on different reference vehicles are cooperated and optimized with the proposed WCL algorithm. The WCL optimized result is compared with that of the conventional LS and LS+1st CC as shown in Fig. 5 and Table III. The conventional LS suffers from large multipath errors, especially the No.5 vehicle. The mean error is 17.71 meters. The LS+ 1st CC excludes the multipath-affected measurements, reducing the positioning error of vehicle 5 to 6.51 meters. However, the 1st CC could be influenced by the simulated random noise. The random noise may coincidently make the high-error measurements consistent. Thus, the health measurements may be mistakenly excluded, resulting a high positioning error for some of the vehicles. The proposed double-layer CC cooperative localization algorithm can use accurate relative distance as constraints and optimize the absolute position of each vehicle. The proposed algorithm reaches a performance that positioning error within 10 meters for each vehicle and improving to 5.33 meters of error in average.

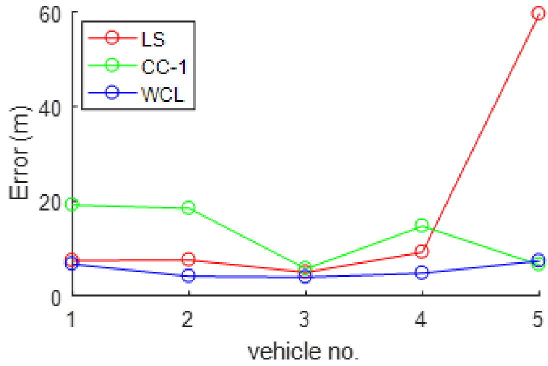

Fig. 5. The error of absolute position of each vehicle with different approaches. LS is the conventional least square positioning, CC-1 is the LS positioning using 1st CC and WCL is the proposed weight cooperative localization algorithm.

TABLE III. THE ABSOLUTE POSITIONING ERROR (M) OF EACH VEHICLE (IN THE UNIT OF METER)

Vehicle	1	2	3	4	5	Mean
LS	7.41	7.53	4.91	9.19	59.53	17.71
CC-1	19.15	18.42	5.67	14.70	6.51	12.89
WCL	6.65	4.07	3.88	4.73	7.32	5.33

To evaluate the reliability of the proposed algorithm, the Monte-Carlo simulation is repeated for 100 runs. The positioning result is shown as Fig. 6. The proposed algorithm can significantly reduce the positioning error comparing with the conventional LS. The proposed WCL can also improve the positioning accuracy when 1st CC still have large error. In 99% of the simulation, the proposed WCL outperform the LS+1st CC. In the other words, the cooperative positioning outperforms standalone positioning.

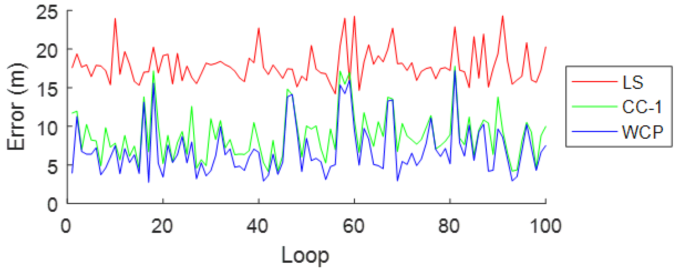

Fig. 6. The mean positioning error of the LS, LS+1st CC and the propsoed cooperative positioning method under 100 runs of Monte-Carlo simulation.

The performance of the proposed cooperated positioning algorithm is further evaluated under three different scenarios:
A) 3 vehicles with healthy GNSS measurements and 2 vehicles with severe multipath-affected GNSS measurements;
B) 2 vehicles with healthy GNSS measurements and 3 vehicles with severe multipath-affected GNSS measurements;
C) 1 vehicles with healthy GNSS measurements and 4 vehicles with severe multipath-affected GNSS measurements.

The positioning result of these scenarios are summarized as Table IV. In all the scenarios, the proposed double-layer CC WCL is outperforming than the other two standalone methods. The proposed algorithm can significantly mitigate the multipath effect and optimize the positioning solution based on cooperating the GNSS measurements of the surrounding vehicle.

TABLE IV. THE ABSOLUTE POSITIONING ERROR OF EACH VEHICLE IN DIFFERENT SCENARIOS (IN THE UNIT OF METER)

Case	Vehicle	1	2	3	4	5	Mean
A 3g2b	LS	7.38	7.64	45.09	7.91	27.33	19.07
	CC-1	12.17	8.31	4.34	3.98	7.27	7.21
	WCL	5.91	6.70	5.82	5.89	4.79	5.82
B 2g3b	LS	12.08	8.94	44.91	26.78	63.23	31.19
	CC-1	8.09	11.74	6.49	5.55	7.92	7.96
	WCL	7.55	8.22	6.05	5.68	5.95	6.69
C 1g4b	LS	12.59	46.83	17.90	28.22	60.08	33.12
	CC-1	17.41	18.15	9.68	12.41	19.91	15.51
	WCL	9.54	5.55	8.37	6.01	5.48	7.00

B. Experimental Results

An experiment is designed to evaluate the performance of the proposed cooperative localization algorithm using real GNSS signals. Five GNSS receivers are used to collect pseudorange measurements at the same time but at different locations. u-blox M8T receivers are used in the experiment. Both GPS and BeiDou signals are used in this experiment. The collected measurements are cooperated by post-processing. The receiver locations are selected as the similar location in the simulation and shown in Fig. 7.

Fig. 7. The selected locations of the five GNSS receivers in the experiment.

Since the sampling time of the pseudorange measurements are not exactly the same for all the receivers (also considering the potential communication latency in V2V), the data of GNSS measurement from different vehicle is synchronized if their time difference is less than 1 second. The absolute positioning errors of the conventional LS, LS+1st CC and proposed cooperative positioning method are shown as Fig. 8 and Table V. As can be seen from Table V, the LS suffers a positioning error of 25.51 meter in average due to the multipath/NLOS effects. By the use of the 1st CC, the mean error is reduced to 11.92m. Finally, the proposed cooperative localization algorithm can optimize all the measurements from the participating vehicles, obtaining accurate solutions that with 10 meters of error in average. In some of the case, the positioning accuracy of WCL may similar to 1st CC result, or even has larger error than that of 1st CC. It is due to the uncommon noise within the measurements that failed to be excluded, this noise may introduce extra error during DD, making the constraint of relative position not reliable. In summary, the performance of the proposed cooperative positioning method is outperforming the other standalone method accordingly both the simulation and experiment results.

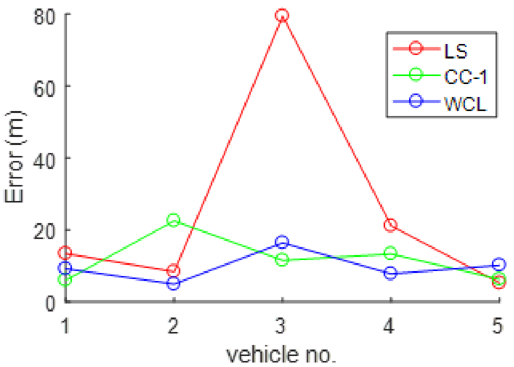

Fig. 8. The experiment result of the absolute positioning error of each vehicular receiver.

TABLE V. THE EXPERIMENT RESULT OF THE ABSOLUTE POSITIONING ERROR OF EACH VEHICULAR RECEIVER (IN THE UNIT OF METER)

Vehicle	1	2	3	4	5	Mean
LS	13.40	8.39	79.43	21.12	5.23	25.51
CC-1	6.00	22.50	11.51	13.31	6.26	11.92
WCL	9.18	4.92	16.39	7.75	10.17	9.68

V. CONCLUSIONS AND FUTURE WORK

The localization accuracy in dense urbans is still a bottleneck, which highly influenced the reliability and safety of the autonomous driving. With the development of multi-GNSS and V2V communication, a novel cooperative localization algorithm based on double-layer CC of GNSS measurements is developed. According to the simulation and experimental result, the 1st CC with LS positioning is able to exclude the inconsistent measurements, especially the multipath affected measurement. Then, the survived measurements are processed to obtain accurate positions of each vehicle. The survived measurements from two vehicles are further applied with DD and conducted with 2nd CC, excluding the inconsistent DD measurements. The accurate relative distance between each vehicle is obtained from 2nd CC and DD, which eliminates the systematic error and mitigates the multipath effect. The relative and absolute positions of ego and surrounding vehicles are cooperated with the proposed WCL, optimizing the shared measurements to optimize the final accurate localization solutions of each vehicle. The proposed algorithm in this study can significantly improve the localization accuracy within 10 meters even in a dense urban environment.

In the future work, since some of the surrounding vehicle measurements may failed to be shared to the ego vehicle, the partially available GNSS measurements situation should be considered. The multi-constellation measurements should be also considered because the measurements of difference vehicle may employ different GNSS receivers. Moreover, the localization accuracy should be further improved to fulfill the autonomous driving requirement. The check exclusion performance should be further improved, ensuring the healthy measurements are not being mistakenly excluded. The cooperative localization algorithm is required to be improved to enhance the final optimized positioning solution accuracy.

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