# UWB/GNSS-based Cooperative Positioning Method for V2X Applications

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**ABSTRACT**

Limited availability of GNSS signals in urban canyons is a challenge for the implementation of many positioning-based traffic safety applications, and V2X technology provides an alternative solution to resolve this problem. As a key communication component in V2X technology, Dedicated Short Range Communication (DSRC) not only allows vehicles to exchange their position, but also traffic safety related information such as real-time congestion, up-to-date accident details, speed limits, etc. This position and traffic information could underpin various traffic safety applications - for instance, lane departure warnings, potential collision avoidance, and traffic congestion warnings. By taking advantage of DSRC, a vehicle in a GNSS denied environment is able to calculate its position using the assistance of other vehicles with sufficient GNSS signals to fix their locations. The concept of cooperative positioning, which is also called collaborative positioning, has been proposed to achieve this goal.

To resolve the locations of a vehicle that is driving in the GNSS denied area, a cooperative positioning solution using integrated Ultra Wideband (UWB) and GNSS is presented in this paper. The methodology of the cooperative positioning solution and proof of concept tests are described. Firstly, the capability of UWB range measurement is tested, followed by the comprehensive assessment of the performance of proposed solution. The results show that by utilising UWB range measurements, better than decimetre accuracy can be achieved even in a kinematic scenario, and that the proposed solution can provide decimetre level 2D location accuracy that satisfies the requirement of traffic safety applications.

**Keywords:** *V2X; cooperative positioning; UWB; range measurement.*

## INTRODUCTION

Providing the advantage of global coverage and relatively reliable accuracy, GNSS is widely used in the fields of civil engineering, the military and transportation. However, GNSS suffers from the signal fading, multipath, obstruction and blockage in urban areas, especially within urban canyons. In the transportation domain, traffic safety is the essential point that needs to be considered. The statistical results demonstrate that around 70% to 80% of traffic accidents occur in the vicinities of road intersections. Compared to the traditional passive measures used to implement traffic safety, such as seat belts and air bags; active traffic safety focuses on the prediction of potential accidents. Due to low GNSS availability and distorted signals in urban canyons, other positioning technologies need to be employed. V2X (a generic name for Vehicle-to-Vehicle and Vehicle-to-Infrastructure communication) plays an important role that links drivers together in Non-Line of Sight (NLOS) scenarios. It offers the opportunity for drivers to have a clear picture of their driving environment [1].

As V2X technology can be used to bridge the communication gap between road users, their exact location and status can be transferred to each other. The remaining problem is how to obtain the positions of the vehicles that are travelling in the GNSS denied environments. Due to poor GNSS signal quality and availability, the concept of cooperative positioning needs to be adopted. Ultra Wideband (UWB) technology not only has the abilities of rejecting multipath and suppression of signal reflection, but also overcomes NLOS situations with its superior penetration characteristics [2]. Besides, UWB can achieve decimetre- or even centimetre-level positioning accuracy with its range observations. In other words, the distances between UWB-equipped road agents or infrastructure can be measured with high positioning performance. If there are enough range measurements (at least two for 2D positioning) from other objects with known coordinates, a vehicle is able to precisely obtain its own coordinates. Based on this coordinate exchange, road users are able to prevent potential collisions in advance.

As discussed in [3], the adoption of V2X technology is due to the urgent need to improve the efficiency and safety of road transportation systems. The authors also discuss the challenges of V2V technology and one of them is how to aid GNSS positioning to achieve better than metre-level accuracy in hostile environments, such as urban canyons. In particular, the lack of GNSS signals is the biggest challenge in such an environment. To constrain the positioning result, an application of vehicle positioning that relies on a road map matching algorithm has been introduced in [4] and decimetre-level accuracy is obtained. In [5], researchers propose a positioning technique with fewer than four GNSS satellites. Utilising the difference of the pseudorange between two satellites, this technique could provide approximately 15 metre positioning accuracy. In [6-13], researchers have investigated the feasibility of using cooperative positioning as a key implementation of position acquisition under V2X scenarios. By transmitting GNSS positions to each other in different driving environments, the positioning quality has been significantly improved. However, V2X technology can only help when the vehicle is able to obtain its own position with enough GNSS satellites.

In [14], the authors propose a method to collect enough GNSS signals by combining two GNSS receivers' observations. It resolves the problem caused by the lack of GNSS signals but the pre-measurement of the baseline between two static receivers limits its implantation in transport. In [15], a novel method in the V2X environment to transmit RTK corrections has been raised. It is feasible for transport applications due to the outstanding performance of RTK technology. However, the monopoly of GNSS positioning cannot provide enough reliability and continuity for traffic safety applications.

To improve the robustness and stability of the positioning solution, multi-sensor integration needs to be considered. A loosely-coupled integration of low-cost GPS/INS and UWB solution is proposed in [16], which can achieve 20 cm accuracy with observable UWB measurements. Removing the INS, a tightly-coupled Kalman filter-based solution that provides approximately 40 cm accuracy is proposed in [17]. Moreover, a Particle filter-based solution is announced in [18] by combining an odometer, GPS and Dead Reckoning (DR) to achieve 20 cm accuracy. In [19], peer-to-peer cooperative positioning has been introduced and the capability of terrestrial ranging has been assessed. To further exploit the excellence of UWB, its ranging measurement is employed in an integration system. In [20], an augmentation method with one UWB base station has been introduced and a multiple UWB base station system is further discussed in [21-25]. In these papers, the UWB devices are only used as static base stations to assist GPS receivers to resolve the integer ambiguity, by combining the UWB range measurements in a tightly-coupled integration with GPS to compute the position of a rover device. In [26-28], bearing measurements are employed to improve the positioning accuracy in a V2V scenario. What is more, different sensor configurations for collaborative driving in urban environments have been assessed in [29].

This paper presents initial results of the experiment to observe one target coordinates using more than two UWB range measurements with known coordinates. To provide precise coordinates a Leica GS10 GNSS receiver and AS10 antenna was attached to the UWB unit, and the lever arm between GNSS and UWB antenna phase centre was also measured. Meanwhile, the positioning solutions from the attached GNSS receiver also act as the ground truth trajectory. Using the idea of triangulation, the target's plane coordinates had to be resolved by following the principle of least squares estimation (LSE). At the start, the accuracy of UWB range measurement was estimated in both static and kinematic scenarios. Furthermore, the availability of UWB range measurements was calculated and the Dilution of Precision (DOP) value was analysed in both scenarios. Finally, the accuracy of the calculated coordinates from the UWB range measurements were assessed by comparison with the results from the GNSS receiver. Some conclusions and future works are detailed at the end of the paper.

## UWB/GNSS Cooperative Positioning

In the following simulated scenario, a target vehicle cannot get its own position because of a lack of visible GNSS satellites. However, this vehicle can determine the location with the support from surrounding vehicles that have enough satellites to fix their coordinate via a DSRC link. Assuming all vehicles have been equipped with UWB units, which provide distances to each surrounding vehicle, the target vehicles position can be calculated. To resolve the unknown 2D coordinates of the UWB mobile unit (the target vehicle), the coordinates of at least two surrounding vehicles, and the ranges between them and target vehicle are necessary. As more than two pairs of ranges and coordinates are used, the number of observations is more than the number of unknowns. The LSE can balance all observations and give a better result. In the LSE, the weights of each unit are treated as the same in this scenario. For post processing, the GNSS derived coordinates are used as the ground truth.

Based on LSE, the location of the UWB mobile unit has a state vector X, defined as:

$$X = \begin{bmatrix} x \\ y \end{bmatrix} \tag{1}$$

And X can be derived as:

$$X = X_0 + \Delta X \tag{2}$$

$$\begin{cases} x = x_0 + \Delta x \\ y = y_0 + \Delta y \end{cases} \tag{3}$$

Where $x_0$ and $y_0$ are the initial values, and $\Delta x$ and $\Delta y$ are the corrections of the state vector X.

Then, the measurement matrix B, weight matrix P and error vector l can be defined as follows:

$$B = \begin{bmatrix} \frac{x_1 - x_0}{\sqrt{(x_1-x_0)^2+(y_1-y_0)^2}} & \frac{y_1 - y_0}{\sqrt{(x_1-x_0)^2+(y_1-y_0)^2}} \\ \frac{x_2 - x_0}{\sqrt{(x_2-x_0)^2+(y_2-y_0)^2}} & \frac{y_2 - y_0}{\sqrt{(x_2-x_0)^2+(y_2-y_0)^2}} \\ \vdots & \vdots \\ \frac{x_n - x_0}{\sqrt{(x_n-x_0)^2+(y_n-y_0)^2}} & \frac{y_n - y_0}{\sqrt{(x_n-x_0)^2+(y_n-y_0)^2}} \end{bmatrix} \tag{4}$$

$$l = \begin{bmatrix} \sqrt{(x_1-x_0)^2+(y_1-y_0)^2} - L_1 \\ \sqrt{(x_2-x_0)^2+(y_2-y_0)^2} - L_2 \\ \vdots \\ \sqrt{(x_n-x_0)^2+(y_n-y_0)^2} - L_n \end{bmatrix} \tag{5}$$

$$P = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} \tag{6}$$

Where $x_n$, $y_n$ are coordinates observed by the GNSS receiver, $L_n$ is the range observations from the UWB device and P is an identity matrix.

According to the principle of LSE, the correction of the state vector is:

$$\Delta X = (B^T P B)^{-1} B^T P l \tag{7}$$

The improved estimation of the UWB mobile unit's location is:

$$\begin{cases} \hat{x} = x_0 + \Delta x \\ \hat{y} = y_0 + \Delta y \end{cases} \tag{8}$$

## DATA COLLECTIONS

### UWB RANGE MEASUREMENT TEST AND STATIC MOBILE UNIT TEST

To figure out the performance of the UWB range measurement, a test has been carried out on the meadow in front of the National College on the Jubilee Campus of the University of Nottingham. Four UWB base stations were set up at the beginning of the trial and their coordinates were determined using a total station and initiated manually. One UWB mobile unit was attached to the top of a pole with a 360° reflective prism, which was tracked by a Leica TS30 robotic total station in real-time. The Leica TS30 robotic total station specifies that it can achieve 3 mm accuracy with a 360° tracking prism [30]. With millimetre-level accuracy, this total station is capable of assessing the performance of the UWB range observations. The pole was carried by a person, and moved in and out of the network that consists of four UWB base stations. A second UWB mobile unit was placed on a tripod to test the range distance between the two UWB mobile units. Both UWB mobile units were connected to a dedicated laptop to store the range observations. The UWB network configuration is shown in Fig.1, and consists of four base stations (blue squares) and two mobile units (red star). Furthermore, the position of the static UWB mobile unit is resolved by the UWB/GNSS cooperative positioning method to prove the concept. In total, four range observations from base stations and one range observation from the other moving UWB mobile unit are gathered to resolve the coordinates of the static UWB mobile unit.

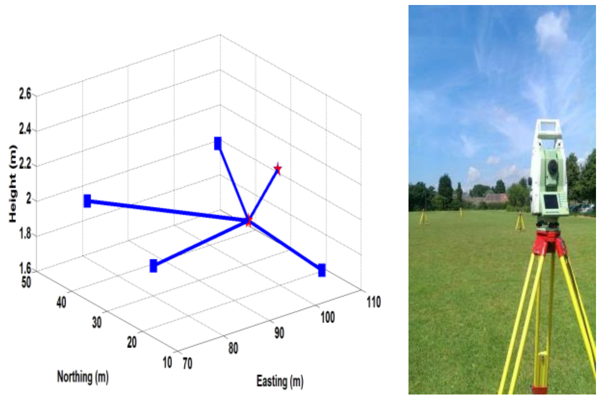


**Fig. 1 UWB network distribution for the field test**

### KINEMATIC UWB/GNSS COOPERATIVE POSITIONING TEST

To further assess the method in a kinematic scenario, an extended test has been conducted on the roof of the Nottingham Geospatial Institute on the Jubilee Campus of the University of Nottingham. The system consisted of 4 GNSS receivers and 6 UWB units. Specifically, two

UWB units were set up as static stations with their coordinates determined by a Leica robotic total station (TS30), and were located on a pillar near to the east side of the roof and on the north edge of the roof. The other UWB units were configured as mobile units to be carried by three people and an electric locomotive. All of them were combined with Leica GS10 GNSS receivers separately, as shown in Fig. 2. An overview of the system is displayed in the plot in Fig. 3.

During the trial, four mobile units were moved along the track for more than 20 minutes. The sampling rates of the UWB units and GNSS receivers were both 1 Hz, and the data from each was collected separately for post-processing and analysis. As the nominal positioning accuracy of the Leica GNSS GS10 receiver is 8 mm in horizontal and 15 mm in vertical, its observations were used as ground truth [31].

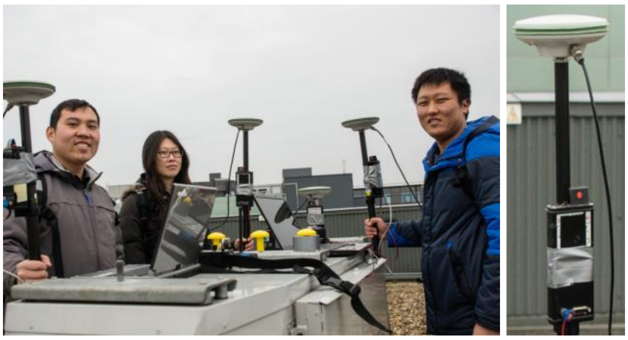

**Fig. 2 Combined GNSS and UWB devices**

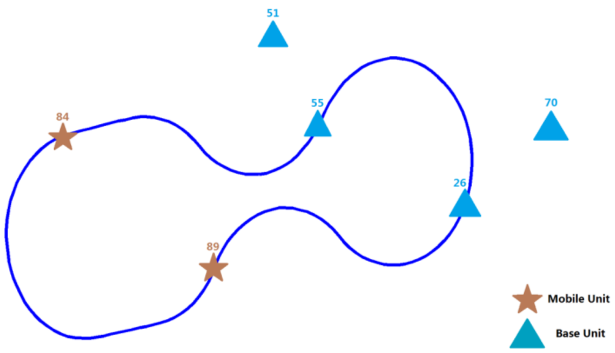


**Fig. 3 Overview of the system**

**EXPERIMENTAL RESULTS AND DATA ANALYSIS**

UWB RANGE ACCURACY ANALYSIS

Combining several short tests together, Fig. 4 draws the comparison of the UWB and total station range measurements. The UWB measurements are generated from two mobile units. In the upper graph in Fig. 4, the UWB range (blue line) matches the total station range (red line) with high precision. The lower graph in Fig. 4 shows the error of the UWB range. Fig. 5 shows the accuracy of the UWB range between the mobile unit and each of the four base units.

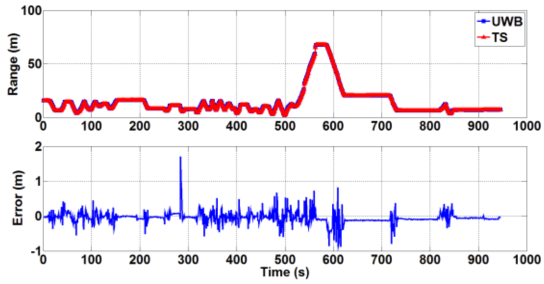


**Fig. 4 Range error between the two mobile units**

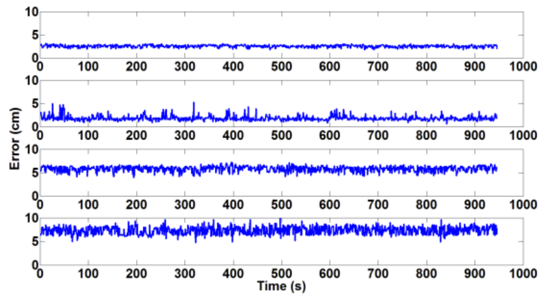


**Fig. 5 Range between the static mobile unit and each base station**

Table 1 demonstrates the statistical results of the range measurement from the static UWB mobile unit. For all five ranges, UWB can provide greater than 90% availability. If both the mobile unit and base stations are stationary, the availability can be further improved to over 95%. In some cases, it could even achieve 99.8% availability. Regarding the range accuracy, UWB can offer better than 7.4 cm range accuracy when both transmitting and receiving units are stationary. In contrast, the range accuracy decreases to 18.8 cm if either transmitting or receiving unit is moving. Moreover, the precision of UWB range measurement is satisfied that is always higher than 1 cm in a static scenario. However it will be down to the decimetre level in a kinematic situation.

Table 1 UWB range accuracies in static scenario

| Unit number | 74 (mobile) | 80 (base) | 84 (base) | 89 (base) | 97 (base) |
|---|---|---|---|---|---|
| Total epoch (s) | 1122 | 1122 | 1122 | 1122 | 1122 |
| Received epoch (s) | 1026 | 1069 | 1120 | 1119 | 1119 |
| Availability (%) | 91.6 | 95.3 | 99.8 | 99.7 | 99.7 |
| Ground Truth (m) | | 18.878 | 27.821 | 13.257 | 28.041 |
| Measured Length (m) | | 18.853 | 27.802 | 13.199 | 27.967 |
| Error (cm) | 18.8 | 2.5 | 1.9 | 5.8 | 7.4 |
| SD (cm) | 18.2 | 0.3 | 0.6 | 0.6 | 0.9 |

## PROOF OF CONCEPT OF THE UWB/ GNSS COOPERATIVE POSITIONING METHOD

Using the input from four static ranges and one mobile range, the coordinates of the static UWB mobile unit are also computed using this cooperative positioning concept. Fig. 6 shows the difference between the computed and pre-measured coordinates in northing and easting directions. It is apparent that the error in the easting direction is worse than northing direction because more movement was made in the easting direction. Comparing the range error of the two UWB mobile units, the coordinate error of the easting direction follows the change of range error. However, the size of the coordinate error is mitigated by using the cooperative positioning method. There is also a spike in both northing and easting errors at around epoch 300, which is mainly attributed to the range error of unit 74. In Table 2, the overall horizontal accuracy achieves 6.4 cm.

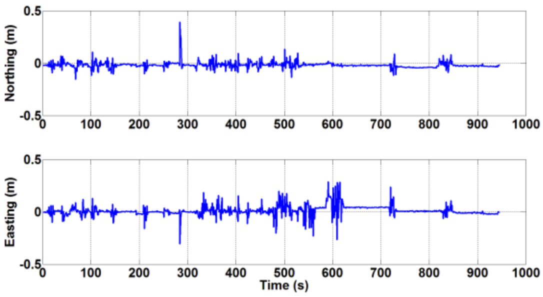


Fig. 6 Computed coordinates

Table 2 Coordinate accuracy of the cooperative positioning method in the static scenario

| | Northing | Easting | Horizontal |
|---|---|---|---|
| RMS (cm) | 3.7 | 5.2 | 6.4 |
| SD (cm) | 3.3 | 5.1 | 4.4 |

## UWB/GNSS COOPERATIVE POSITIONING PERFORMANCE IN A KINEMATIC SCENARIO

In Fig. 7 the blue line shows the raw UWB range data. Firstly, the outliers, the range measurement exceeds the given threshold, are removed from the raw UWB range data. The null data caused by the loss of data and outlier removal, which is shown as the detached blue circle, is interpolated to produce the smoothed data (red line).

As all UWB units are combined with individual GNSS antennas, the range (excluded the beginning static data) between each pair of UWB units is computed and shown as a blue line in Fig. 8. Compared to the GNSS range (red line), the data quality is much improved, and the difference between the UWB and GNSS ranges are shown in Fig. 9.

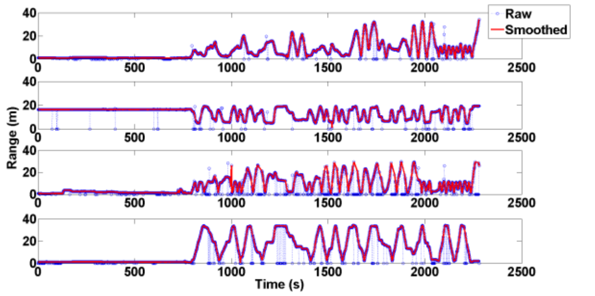


Fig. 7 Smoothed UWB ranges

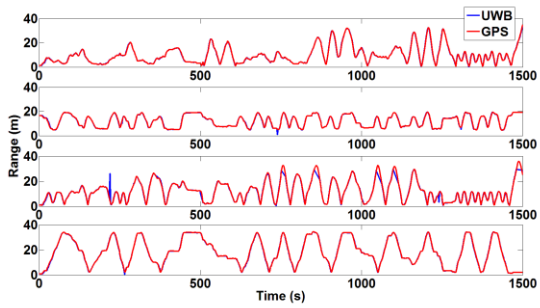


Fig. 8 Smoothed range vs. GNSS

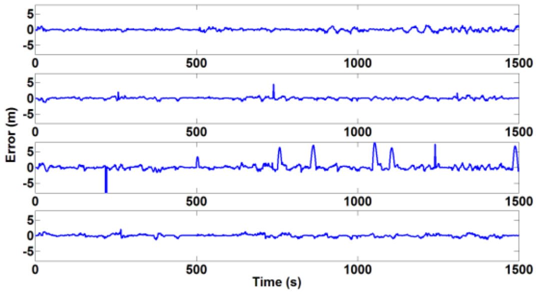


**Fig. 9 Error of smoothed UWB range**

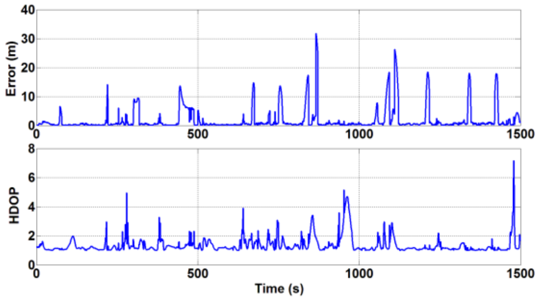


**Fig. 10 Horizontal error vs. HDOP**

The statistical results of ranges between unit 89 and other units are shown in Table 3. Removing the outliers from the raw data, all UWB range availabilities are around 90%, except for unit 55 at 75%. After interpolating the raw data, the range accuracies of unit 26, unit 51 and unit 70 are 39.44 cm, 34.92 cm and 34.49 cm, respectively. On the other hand, the range accuracy of unit 55 is only 1.47 metres. The reason for the bad performance of unit 55 is that it was carried by a person, making it difficult to keep vertical and causing different orientations of the UWB antenna. Table 4 shows the accuracy of the cooperative positioning solution which is 4.57 metres for the whole trial. To find out how good the cooperative positioning solution could be, two data samples have been selected and are discussed later.

**Table 4 Overall coordinate accuracy of the cooperative positioning method in a kinematic scenario**

| | Northing | Easting | Horizontal |
|---|---|---|---|
| **RMS (m)** | 2.0 | 4.0 | 4.5 |
| **SD (m)** | 2.0 | 3.9 | 4.1 |

Furthermore, a comparison between horizontal accuracy and HDOP is shown in Fig. 10. In the upper graph, it is found that the poor overall accuracy is mainly contributed by several spikes. What is more, the HDOP values in the lower graph do not significantly correlate with the horizontal accuracy. Unless all contributed UWB ranges achieve a similar accuracy level, the geometry of the UWB units may not essentially affect the overall coordinate accuracy.

Two data samples including laps of the electric locomotive circuit have been extracted and are shown in Fig. 11 and Fig. 12. In both Fig. 11 and Fig. 12, the red stars represent GNSS coordinates for each epoch, and the blue squares reflect the coordinates computed by the UWB/GNSS-based cooperative positioning method. The trajectory of target UWB unit is clearly illustrated, though there are few outliers.

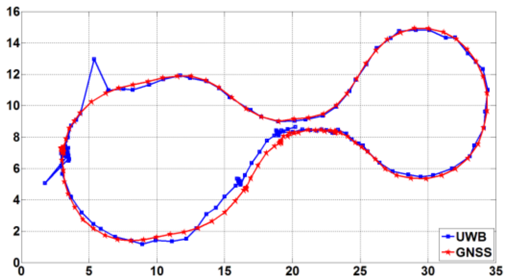


**Fig. 11 Sample lap 1**

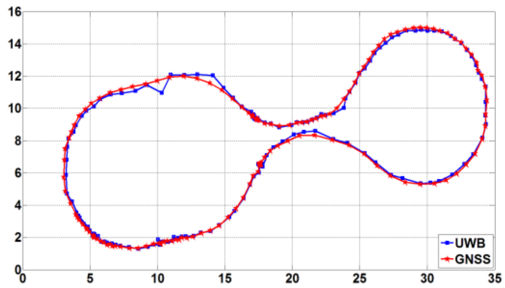


**Fig. 12 Sample lap 2**

**Table 3 UWB range accuracies in kinematic scenario**

| | 26 (moving) | 51 (static) | 55 (moving) | 70 (static) |
|---|---|---|---|---|
| **Total epoch (s)** | 1500 | 1500 | 1500 | 1500 |
| **Received epoch (s)** | 1467 | 1470 | 1437 | 1440 |
| **Availability (%)** | 97.80 | 98.00 | 95.80 | 96.00 |
| **Outlier removal (s)** | 1351 | 1426 | 1126 | 1311 |
| **Availability (%)** | 90.07 | 95.07 | 75.07 | 87.40 |
| **RMS (cm)** | 35.0 | 31.5 | 127.0 | 48.5 |
| **SD (cm)** | 34.9 | 34.5 | 125.7 | 47.9 |

The computed UWB trajectory conforms to the GNSS trajectory, and the numerical results are given in Table 5 and Table 6. In lap 1, the range accuracies of the four units are 63.4 cm, 32.5 cm, 64.6 cm and 38.7cm. The range accuracies in lap 2 are 9.8 cm, 11.0 cm, 20.9 cm and 18.7 cm. Suffered from an unstable UWB antenna, UWB can almost provide better than 70 centimetre range accuracy. In Table 6, the accuracy of lap 2 data is better than lap 1, and the overall horizontal accuracies in lap 1 and lap 2 are 71.1 cm and 18.6 cm, respectively.

**Table 5 UWB range accuracy of sample data**

| Unit Number | 26 (kinematic) | 51 (static) | 55 (kinematic) | 70 (static) |
|---|---|---|---|---|
| **Lap 1** | | | | |
| **RMS (cm)** | 63.4 | 32.5 | 64.6 | 38.7 |
| **SD (cm)** | 63.6 | 32.6 | 63.7 | 37.1 |
| **Lap 2** | | | | |
| **RMS (cm)** | 9.8 | 11.0 | 20.9 | 18.7 |
| **SD (cm)** | 9.7 | 10.2 | 20.9 | 17.3 |

**Table 6 Sample data coordinate accuracy of cooperative positioning method in kinematic scenario**

| | Northing | Easting | Horizontal |
|---|---|---|---|
| **Lap 1** | | | |
| **RMS (cm)** | 50.4 | 50.1 | 71.1 |
| **SD (cm)** | 45.4 | 49.7 | 46.9 |
| **Lap 2** | | | |
| **RMS (cm)** | 13.0 | 13.3 | 18.6 |
| **SD (cm)** | 12.0 | 13.3 | 11.7 |

## CONCLUSION AND FUTURE WORK

In conclusion, the UWB range measurement can always achieve better than 70 centimetre accuracy. If both transmitting and receiving UWB units are stationary, better than 10 cm accuracy is achieved. When one UWB unit is continuously moving, the UWB range accuracy decreases to approximately 30 cm. Furthermore, the accuracy is degraded to 70 centimetres if both transmitting and receiving UWB units are moving. The UWB range measurement suffers from spikes and outliers, and raw data smoothing is necessary to improve observations. UWB could complement GNSS when it cannot provide a GNSS-only solution by using the cooperative positioning solution. The horizontal accuracy of the cooperative positioning solution achieved 20 centimetre accuracy in a kinematic scenario, and the UWB range accuracy is the most important element as oppose to HDOP for the overall accuracy.

For future work, the characteristics of the UWB spikes will be investigated and analysed to develop a more effective filtering method. With similar range accuracies of UWB and GNSS carrier phase measurements, a tightly-coupled UWB/GNSS approach is being developed.

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