GNSS Moving Baseline Solutions Tested for Collision Avoidance Spatial Parameters

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ABSTRACT

The collision avoidance function of automatic driving vehicles is a critical issue for their operational development. As an indispensable system component for intelligent vehicles, GNSS (Global Navigation Satellite System) devices provide real-time positioning required by navigation, and capture collision spatial parameters between vehicles. In the feasible GNSS solution, the moving baseline (MBL) mode can operate without the need for a base station, but only using the GNSS observation data received by the vehicles. Through data transmission, the solution can be directly obtained by the master vehicle. In this study, the most common front-rear collisions are studied using a master vehicle and a rover vehicle. First, the magnitude of the calculation error of the collision avoidance parameters was discussed when the two vehicles were static. The test results show that the distance error of MBL solution is 0.23 m, the relative heading error is 0.10°, the relative speed error is 0.20 km/hr, and the fixed solution ratio of integer ambiguity is 99%. Then, a kinematic driving test was carried out in the urban area, and the test results show that the collision avoidance parameters solved by MBL can also effectively interpret various driving situations.

Keywords: GNSS, collision avoidance, spatial parameters, moving baseline

GNSS 移動基線法測算避撞空間參數

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摘　要

自動行駛載具的避撞功能，將是其運作發展所須面對的重要課題。GNSS 定位裝置是智慧型載具不可或缺的系統元件，除可提供導航所需之即時定位外，亦有獲取載具之間避撞空間參數之運用能力。在可行之 GNSS 定位解算方法中，移動基線法(MBL)在運作時可無須使用基站，而僅利用載具接收之觀測資料，再透過資料的傳遞，即可於主載具上直接進行解算。本研究以最常發生的前後碰撞為案例，採用二台分別代表主車及來車之行車情境，先以二車固定不動方式探討避撞參數解算之誤差量級，由測試得知 MBL 提供之相對距離誤差為 0.23 m、航向誤差為 0.10°、速度誤差為 0.20 km/hr，且整數未定值之固定解比率可達 99%。另於都會區街道實施動態行車之測試成果顯示，MBL 所解算之避撞相關參數亦具有效之判釋能力。

關鍵詞：全球導航衛星系統、避撞、空間參數、移動基線法

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I. INTRODUCTION

In the present and near future, collision avoidance will be a critical development issue for automatic driving vehicles, such as ground self-driving vehicles or airborne drones. Even when the era of automatic driving has not yet fully arrived in the present, the collision avoidance operation of mobile vehicles is one of the important solutions for the development of related systems.

It is generally believed that the best way to reduce injury in road accidents is to avoid collision between vehicles, which gives rise to the so-called Collision Avoidance Support System (CASS). The CASS can be developed with different perspectives as follows [1].

(1) Conventionally in automatic systems, it is necessary to estimate the safe distance between the master vehicle and adjacent vehicles, and to warn the drive system, which is usually accomplished by radar and vision systems. However, such systems are often limited by the visibility and sensing capabilities of sensors, can only detect and provide status messages of adjacent vehicles, and may result in higher device costs.

(2) The CASS system can form a collision avoidance operational system based on infrastructure construction by installing warning and sensing components on the road sides. However, such information provided by road infrastructure can be delivered to drivers through meters, but it often fails to meet the real-time demand, meaning it is still less effective than mounting the sensors on vehicles.

(3) A new concept is to operate through a Cooperative CASS (CCASS), which is formed between vehicles. The master vehicle can track the adjacent vehicles and detect possible dangerous conditions depending on the inter-vehicle coordination levels. Of course, the requirement of this operational mode is that the status information of the adjacent vehicles can be transmitted and received periodically by wireless communication, the so-called V2X consisting of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) [2][3].

In order to increase vehicle safety, vehicles are usually mounted with embedded systems to control the anti-collision control system, which consists of the vehicle, GNSS module, and Dedicated Short Range Communication (DSRC) [4]. In addition to the navigation function, the GNSS module can provide precise information regarding vehicle position, distance, speed and heading to the vehicles in a working environment for a longer range and a longer period, with shorter time intervals.

GNSS is certainly not the only spatial sensing tool available to provide collision avoidance information to vehicles. Other tools, such as LiDAR, radar, stereoscopic images, or ultrasound, can play different sensing functions; however, they are easily affected by different operational environments or system conditions [5].

Despite the impact of the data update rate and observation restriction of GNSS sensors, among the many sensors available, the main advantage of GNSS sensors is its broad operational range. If the wireless communication range between vehicles can be expanded, such as DSRC’s 300-1000 m, the sensing range can be expanded. In addition, when the satellites are visible enough, GNSS can be effectively used to expand the sensing range and reduce the reaction time.

Therefore, if the GNSS sensors can further cooperate with applicable positioning modes, the spatial information required for the collision avoidance function between vehicles can be obtained through the GNSS system; thereby, expanding the other operational functions of the GNSS system in automatic driving apart from navigation. For example, a vehicle traveling on a highway can realize the speed change or lane switch information from GNSS, which can be used for the detection and analysis of dangerous collision scenarios.

The main purpose of this study is to explore the error magnitude in the avoidance collision spatial parameters between vehicles and the parameter interpretation capability of the GNSS positioning module mounted on the vehicles.

II. GNSS MOVING BASELINE SOLUTION

According to the research of applying

GNSS positioning technology to the determination of vehicle collision avoidance parameters, in order to obtain the spatial motion relationship between the master vehicle and the rover vehicle, the data can be applied in two modes. In the first mode, both vehicles perform positioning calculation after receiving the GNSS observations, and the rover vehicle transmits its positioning coordinates to the master vehicle, and then, the main vehicle converts the positioning coordinates of the two vehicles into collision avoidance parameters. In the second mode, after both vehicles receive the GNSS observations, the rover vehicle transmits the original data to the master vehicle, which will be positioning based on the collected data of the two vehicles and solve the required collision avoidance parameters.

Regarding the evaluation of the two modes, the transmission of GNSS positioning coordinates (the first mode) is featured by lower data transmission volume; while the transmission of GNSS original observations (the second mode) retains the advantage of data application and added value. For example, the UAV transmission standard, as developed by the Society of Automotive Engineers (SAE), advocates the transmission of GNSS original observation data, which can improve the capability of integrating data with other systems in the interfered environment; thereby, strengthening collision avoidance operations in an increasingly congested space [6].

In the first mode, as based on the transmission of GNSS positioning coordinates, the GNSS positioning techniques include: single point positioning (SPP) and precise point positioning (PPP) in the absolute positioning, and real time kinematic (RTK) in the relative positioning. In the second mode, as based on the transmission of GNSS original observations, the moving baseline (MBL), which is less frequently applied in relative positioning, can be used to obtain relative baseline estimations, such as horizontal distance, slant distance and heading, between vehicles [7].

The MBL positioning mode has been applied in the landing system of aircrafts, the collision avoidance system of railways, the aerial refueling system of aircrafts, the safety warning system of approaching objects and the automatic docking system of ships through GNSS [8][9][10]. Since aircrafts and ships are all moving objects, the relative positioning solution of traveling vehicles, as discussed in this study, share a similar motion mode. Therefore, it is promising to apply the MBL positioning mode in obtaining the collision avoidance parameters of traveling vehicles.

The positioning precision of RTK can reach the centimeter level, that is suitable for use in the related field of Connected and Autonomous Vehicles (CAVs) [11]. However, its operational process must be supplemented by a single base station or a reference network, which is possible to increases the operational burden of the system. Since the master vehicle and the rover vehicle discussed in this study are all moving objects, and the main requirement is only the relative spatial relationship between the two vehicles, the MBL method in GNSS relative positioning techniques can play a certain role in the calculation of collision avoidance spatial parameters (as shown in Fig. 1).

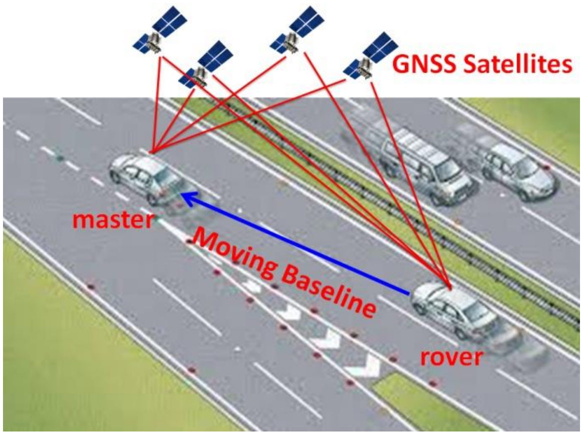

Fig.1. Application scenario of MBL positioning mode in acquiring collision avoidance information

When MBL is adopted to obtain results, no additional differential data from reference stations is required. Although the acquisition of the absolute positioning coordinates through MBL method may only be equivalent to the solution precision of the SPP mode, the relative spatial position between the master vehicle and the rover vehicle can still quickly converge to the precision of the 0.05-0.20 m level [7][12], that is expected to meet the so-called “where in lane" accurary requirement of 0.5 m for the intelligent transportation system (ITS) applications such as driver monitoring and collision avoidance [13].

When the GNSS observation is applied to calculate the relative positioning in the MBL method, the basic phase equation for the GNSS receivers (a, b) mounted on each of the two vehicles and one of the satellites (i) can be formed, as follows:

$$\phi_a^i(\tau) = \frac{f}{c}\rho_a^i(T) - f\,(d\tau_a(\tau) - dt^i(t)) + N_a^i + d_{atm} \quad (1)$$

$$\phi_b^i(\tau) = \frac{f}{c}\rho_b^i(T) - f\,(d\tau_b(\tau) - dt^i(t)) + N_b^i + d_{atm} \quad (2)$$

where, t, τ, T are the time in the satellite time system, the receiver time system and the GNSS time system, respectively, ϕ is the observed carrier phase, c is the speed of the electromagnetic wave in vacuum, f is the frequency of satellite signals, ρ is the geometric distance between the receiver and the satellite, dτ is the clock error of the receiver, dt is the clock error of the satellite, N is the integer ambiguity and d_{atm} is the atmospheric error.

Then, the two basic phase equations are subtracted to form the single difference equation, as follows:

$$\phi_{ab}^i(\tau) = \frac{f}{c}\rho_{ab}^i(T) - f\,d\tau_{ab}(\tau) + N_{ab}^i + d_{atm} \quad (3)$$

When the two single difference equations formed by the two GNSS receivers (a and b) and the two satellites (i and j) are subtracted, the double difference equation used in the GNSS positioning solution can be formed, and its simplified form is, as follows:

$$\phi_{ab}^{ij} = \frac{f}{c}\rho_{ab}^{ij} + N_{ab}^{ij} \quad (4)$$

where, the left side of the equation is observed and the right side of the equation contains the unknown variables to be determined by the positioning solution. It expands, as follows:

$$\phi_{ab}^{ij} = \frac{f}{c}(\rho_b^j - \rho_a^j - \rho_b^i + \rho_a^i) + N_{ab}^{ij} \quad (5)$$

Since ρ is the geometric distance between the receiver and the satellite, it is also a 3D coordinate function of the ground receiver and the satellite; for example

$$\rho_a^i = \left[(X^i - X_a)^2 + (Y^i - Y_a)^2 + (Z^i - Z_a)^2\right]^{1/2} \quad (6)$$

where, (X^i, Y^i, Z^i) is the coordinate of satellite i and (X_a, Y_a, Z_a) is the coordinate of receiver a.

In practical scenarios, the coordinates of satellites i and j can be obtained from broadcast or precise ephemeris, while the coordinates of receiver a are regarded as the master baseline station (the master vehicle), which can be positioned by SPP mode. Therefore, the remaining unknown variables only include the coordinates of receiver b (the rover vehicle), and the integer ambiguity of the phase difference between a and b.

To calculate the spatial information in need, the solved 3D geocentric coordinate of (X,Y,Z) can then be first converted to the curvilinear geodetic coordinate of latitude, longitude and height, and further transformed to the topocentric local coordinate or transverse Mercator projection coordinate [14][15].

III. DEFINITION OF COLLISION AVOIDANCE PARAMETERS

When SPP, PPP, RTK or MBL is applied in the GNSS positioning mode, the baseline vector between the master vehicle and the rover vehicle can be established directly or indirectly. With the spatial relationship formed by this baseline, the required basic spatial parameters of the collision avoidance operation can be calculated. In this study, the collision avoidance parameters include relative distance, heading and speed between the two vehicles. The related definitions and calculation methods are, as follows:

(1) Relative distance

This distance parameter is defined as the distance (S) of the rover vehicle relative to the master vehicle at epoch i, as follows:

$$S_i = \sqrt{\Delta n_i^2 + \Delta e_i^2 + \Delta u_i^2} \quad (7)$$

It is suggested that this parameter should be calculated by the 3D coordinate difference of the two vehicles (Δn, Δe, Δu) instead of the 2D coordinate difference (Δn, Δe), because the spatial distance (non-planar distance) is more effective to reflect the converted collision avoidance warning time when the height changes dramatically. In addition, the change of this parameter can reflect the changes in the distance between the two vehicles, such as maintaining the same distance, shortening the distance or increasing the distance.

(2) Relative heading

The heading does not refer to the heading of the vehicle itself, but to the azimuth (α) of the rover vehicle relative to the master vehicle at epoch i. The calculation formula is using the plane coordinate difference , as follows [16]:

$$\alpha_i = \tan^{-1}\frac{\Delta e_i}{\Delta n_i} \tag{8}$$

The azimuth provided by this formula is the azimuth of the heading of the rover vehicle relative to the heading of the master vehicle. In terms of application, this parameter can reflect the changes in the headings of the two vehicles, such as maintaining the same heading, turning or changing lanes.

(3) Relative speed

The speed does not refer to the driving speed of the vehicle itself, but the difference in vehicle speed (ΔV) of the rover vehicle relative to the master vehicle at epoch i. The calculation formula is, as follows:

$$\Delta V_{ij} = \frac{\Delta S_{ij}}{\Delta t_{ij}} \tag{9}$$

Where time interval (Δt) between two consecutive epochs i and j is used to calculate the distance change (ΔS) at the continuous epochs. In terms of application, the changes in this parameter can reflect the changes in the speed of the two vehicles, such as maintaining the same speed or changing the speed difference.

For example, when the relative distance becomes shorter, the rover vehicle is closer to the master vehicle, and a collision becomes more possible; when the relative heading changes within a certain range, the rover vehicle may change its driving lane; when the relative speed is zero, the rover vehicle is at the same speed as the master vehicle, and collision becomes less possible.

IV. TESTS AND RESULTS

In this study, the GNSS observations were acquired from GPS and GLONASS dual-frequency data, which was recorded by every second (1Hz), and the post processing software was NovAtel GrafNav Version 8.60 [17]. The output in the MBL solution includes: time, latitude, longitude and elevation of the master vehicle, latitude and longitude of the rover vehicle as well as the azimuth, horizontal distance, slant distance, horizontal error, elevation error, quality index and status of integer ambiguity resolution, etc.

In order to analyze the relevant test results, the most common front-rear collision was studied [18]. Two GNSS receivers representing the master vehicle and the rover vehicle were adopted, and four tests were performed. The related test cases are listed in Table 1.

Table 1. Test cases and contents

Case	Motion pattern	Description of contents	Data (1 Hz)	Distance between two vehicles
1	both vehicles were static	relatively short distance	about 500 epochs	about 100 m
2	both vehicles were static	relatively long distance	about 3600 epochs	about 2000 m
3	one vehicle was static and the other was moving	the moving vehicle travelled along the expressway with good satellite visibility	about 3000 epochs	about 60-6500 m

4	both vehicles were moving	the moving vehicle travelled along the downtown roads with poor satellite visibility	about 450 epochs	about 0.5-50 m

In the test cases listed in Table 1, the vehicles in the first case and the second case were static, but the relative distance was different. The purpose is to evaluate the error of the parameter estimation, as provided by different GNSS solution modes. For the third case, one vehicle was moving and the other was static; therefore, the third case can be used to check the solution of the MBL method in the semi-kinematic driving state. Regarding the fourth case, both vehicles were moving, thus, the fourth case can interpret the real motion situation in the MBL solution.

4.1 Test with both Vehicles Static

For the tests of the two cases with both vehicles static, the distance and heading converted from the GNSS static results with higher precision can be regarded as the standard. Along with the relative speed of zero, they can be used to evaluate the root mean square (RMS) error of the collision avoidance parameter, as converted from different modes of GNSS solution. The GNSS modes evaluated in this stage include SPP, PPP, PPK and MBL, in which PPK is post processing kinematic and adopts the same algorithm as the single base station of RTK [19].

In the case of the MBL solution mode, the errors provided by the two cases of GNSS test data were carried out. The results with more epochs of case two are selected and plotted, as shown in Fig. 2. To explore precision, the average errors of the two cases with four GNSS modes were obtained, as shown in Table 2, and compared, as shown in Fig. 3.

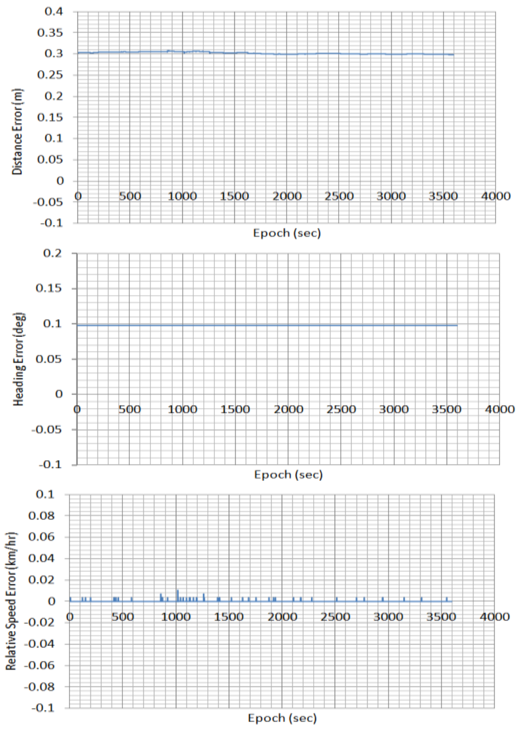

Fig.2. Error in the MBL solution with both vehicles static of case 2 for distance, relative heading and relative speed, respectively

Table 2. Average errors of case 1 and case 2 with both vehicles static

Modes	Error			Success rate (%)
	Dist. (m)	Rel. heading (deg)	Rel. speed (km/hr)	
SPP	1.41	0.55	1.61	N/A
PPP	0.90	0.34	0.04	31.3
PPK	0.16	0.11	0.28	97.2
MBL	0.23	0.10	0.20	99.4

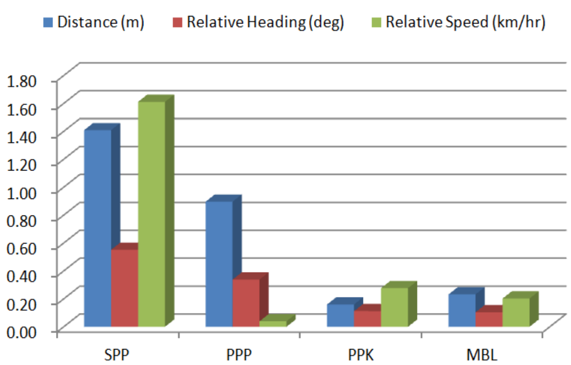

Fig.3. Comparison of average errors with both vehicles static

According to the above results of the both vehicles static tests, as provided by two baselines with different lengths, the pseudo-range based SPP solution error was worse than the other three positioning modes using the carrier phase observable; in addition, the single point mode of PPP solution error was worse in the distance and heading parameters than those of the PPK and MBL based on the relative positioning mode. Furthermore, the fixed solution ratio of integer ambiguity resolution, ie. the success rate, was only about 31% for PPP.

In addition, in the performance comparison of PPK and MBL, the MBL positioning mode was only slightly worse than PPK, by 0.07 m, in the distance error, but better than PPK in the performance of two other parameters. Moreover, the success rate was also close to 100% for MBL.

Regarding the MBL solution, based on the average estimation error of the collision avoidance parameters from the two static tests, the error of distance ranged between 0.16 m and 0.30 m, the error of relative heading ranged between 0.10° and 0.11°m, and the error of relative speed ranged between 0.00 km/hr and 0.40 km/hr. If the ITS required positioning accuracy of bettern than 0.5 m is referred [13], the distance error of less than 0.3 m estimated from the test is satisfied. It is believed that the MBL solution has the effective capability to provide collision avoidance warning parameters.

4.2 Test with One Vehicle Static and the other Moving

Regarding the test of the third case with one vehicle static and the other moving, the GNSS static solution could not be performed; therefore, the PPK solution was treated as the standard, to explore the performance of MBL in solving the semi-kinematic state of GNSS data. During the GNSS observation, the master vehicle was static on the university campus, while the rover vehicle travelled on the expressway along an urban ring road, and the path is shown in Fig. 4. The differences between the estimation of MBL and the standard value of PPK are shown in Fig. 5. The RMS values of a total of 3,000 epochs are shown in Fig. 6.

Fig.4. Test path with one vehicle static (blue mark) and one other moving (red mark)

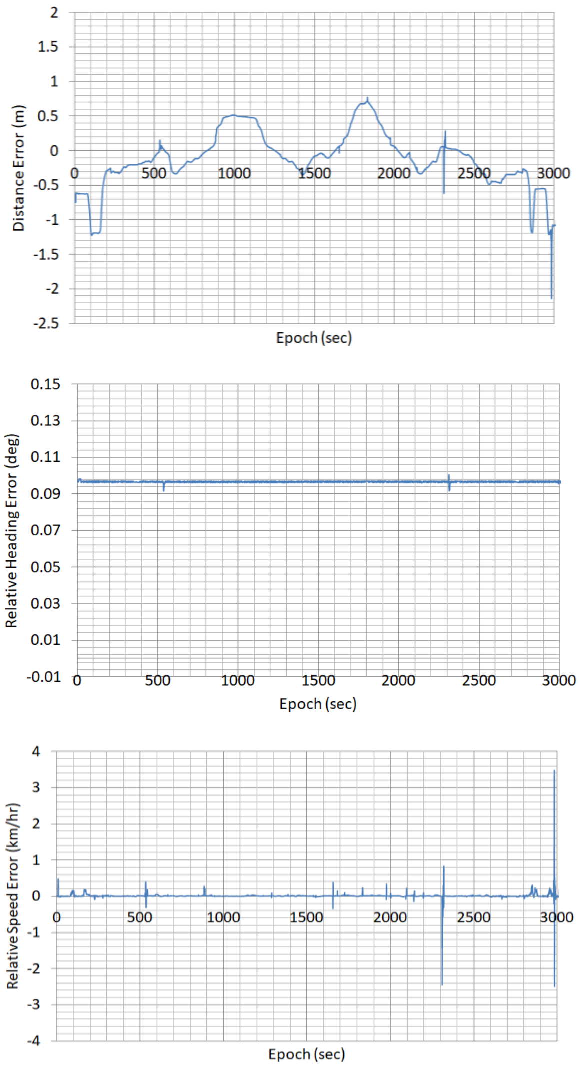

Fig.5. Parameter difference between MBL and PPK solution with one vehicle static and one other moving for distance, relative heading and relative speed, respectively

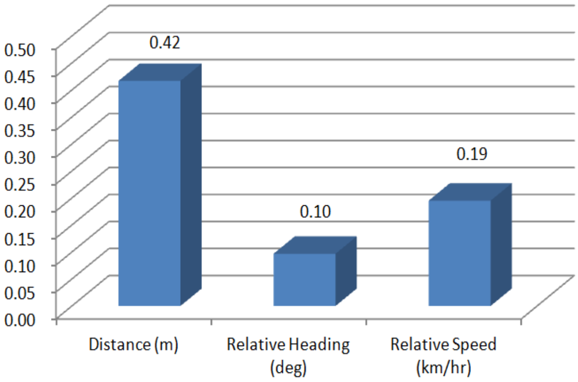

Fig.6. RMS values of the parameter difference between MBL and PPK solution with one vehicle static and one other moving

In the above semi-kinematic test results with one vehicle static and one other moving, the success rates of both the PPK and MBL solutions were 100%. Under this condition, the difference between the MBL and PPK solutions was slightly enlarged 0.42 m in distance, but still less than 0.5 m. The differences in the other two parameters were similar to the estimation errors with both vehicles static. The MBL solution is proved to be still valid and feasible in solving collision avoidance parameters when the vehicles are moving.

4.3 Test with both Vehicles Moving

The test of the fourth case with both vehicles moving was close to the road driving of the two vehicles. In the acquisition of GNSS data, the master vehicle and the rover vehicle were simulated by two motorcycles, as shown in Fig. 7, which travelled on a general road with poor satellite visibility (see Fig. 8).

Fig.7. Photo of test with both vehicles moving

Fig.8. Test route with both vehicles moving

Since this set of MBL solution is based on the two vehicles moving, the errors of the estimated parameters are not capable of effectively evaluated. The collision avoidance parameters solved with kinematic data in this case, its application capability was directly examined. Regarding the MBL solution, the independent coordinates of two vehicles in a representative time period are shown in Fig. 9.

The test results, as shown in Fig. 9, illustrate the changes in the relative spatial positions of the two vehicles during the observation period. Specifically, the two vehicles travelled from the upper right to the lower left, and the rover vehicle first approached the master vehicle from the left rear (referred to ❶). Then, the two vehicles met (referred to ❷), simulating the state of the two vehicles approaching a collision. Next, the rover vehicle overtook the master vehicle in the left lane (referred to ❸), and returned to the same lane in front of the master vehicle (referred to ❹).

Fig.9. Changes in relative positions of two vehicles in a certain period based on the MBL solution (blue circle is the master vehicle and red circle

is the rover vehicle)

To further analysis of the scenario with both vehicle moving on the road, the numbered data are shown in Fig. 10, Fig. 11 and Fig. 12 for the three collision avoidance parameters obtained by MBL solution.

Fig. 10 can reveal the change in distance between the two vehicles, such as increasing (the value becomes higher), reducing (the value becomes lower) and approaching (the value is close to zero). Fig. 11 can show that the change in the relative heading of the two vehicles, such as maintaining heading (maintain constant), turning (higher value changes), changing lanes (lower value changes) and turning successively (after the higher value changes, it is pulled back to the set value). Fig. 12 can demonstrate the change in the relative speed of the two vehicles, such as maintaining constant speed (value is zero) and changing the speed difference (positive or negative values increase or reduce). However, the parameter was determined by the change in the relative distance over a unit time; therefore, when the positive value of the relative speed difference is higher, it cannot judge whether the master vehicle becomes faster or the rover vehicle becomes slower.

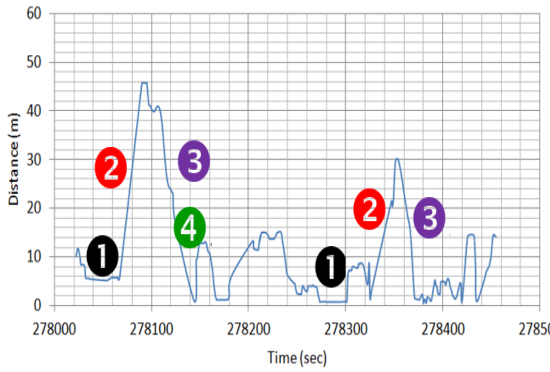

Fig.10. Traveling scenario referred to distance parameter

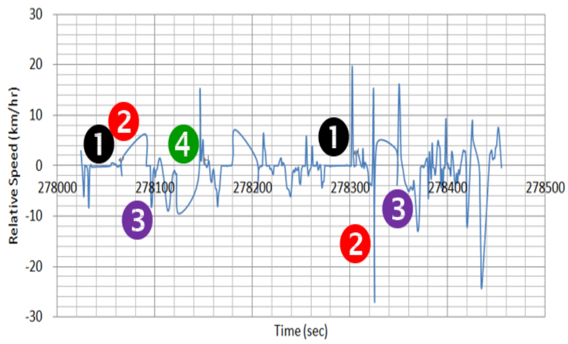

Fig.11. Traveling scenario referred to relative speed parameter

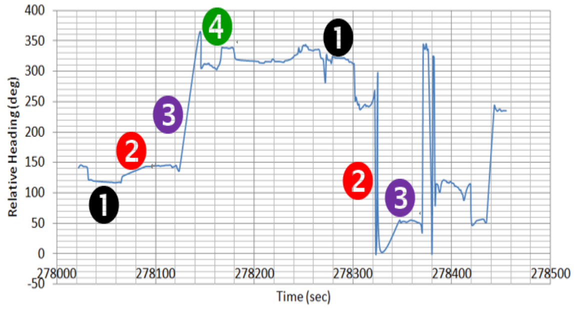

Fig.12. Traveling scenario referred to relative heading parameter

The relevant representative content of the interpretation is described in Table 3.

Table 3. Analysis contents of traveling scenario

No.	Description of scenario	Start epoch	Description of parameter
❶	travel with constant distance	278050 278280	the distance is constant, the relative speed is zero and the relative heading only changes slightly.
❷	increase the distance	278070	the distance is increased, the relative speed changes greatly and the relative heading only changes slightly (same heading).
		278330	the distance is increased, the relative speed changes greatly and the relative heading changes greatly (making turns).
❸	reduce the distance	278090	the distance is reduced, the relative speed changes greatly and the relative heading changes greatly after epoch 278120

			(making turns).
		278350	the distance is reduced, the relative speed changes greatly and the relative heading only changes slightly (same heading).
❹	rover vehicle overtakes	278140	the distance is first reduced and then increased, the relative speed changes greatly and the relative heading only changes slightly (same heading).

V. CONCLUSIONS AND SUGGESTIONS

In this study, as the GNSS satellite positioning technology has the advantages of acquiring spatial positions at different distances, it was applied in solving the spatial parameters required for collision avoidance warning, and the positioning modes with better operational efficiency were evaluated to further expand the application of GNSS positioning.

The positioning mode of MBL does not require a GNSS base station, and it is only required to transmit the observation received by the rover vehicle to the master vehicle, and then, complete the positioning solution and parameter determination on the master vehicle. The static and half-kinematic test results show that the success rate of the fixed ambiguity resolution is almost 100%, the relative distance error is lower than 0.30 m, which can meet the related ITS requirement of 0.5 m in positioning accuracy, the relative heading error is lower than 0.11° and the relative speed error is lower than 0.40 km/hr. Moreover, the collision avoidance parameters provided by the kinematic driving test, and through the comprehensive application of the three related parameters, the corresponding driving scenarios were effectively interpreted.

This paper has completed the relevant tests and evaluations on the applicability of the MBL method in solving collision avoidance parameters. In practice, it is necessary to change the computation mode from post-processing to real-time. As long as the GNSS observations can be exchanged between the vehicles using any feasible communication transmission operation, the MBL method means no big difficulty in application.

When GNSS positioning and collision avoidance parameters are actually applied to the automatic vehicle navigation, there are still some details that must be further clarified, such as the optimal time interval for parameter calculation, the optimization of parameter combinations and the calculation of collision warning time, etc. In addition, the wireless transmission protocol for GNSS data transmission on-board, the definition of complex collision models and system development combined with other sensors, such as IMU, LiDAR, video, pseudolite and beacon, etc., are all profound issues for constructing an integrated collision avoidance sensing system.

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