Vehicles Positioning in Tunnel: A Real-Time Localization System Using DL-TDOA Technology

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Abstract

Due to the dim light in the tunnel and the characteristics of natural electromagnetic shielding, drivers are prone to accidents in the tunnel and are unable to inform the navigation system in time. Therefore, it is still a bottleneck in the field of intelligent transportation how to obtain real-time vehicle position information and vehicle state information when the vehicle is running at high speeds in the tunnel. In this paper, a new technology is proposed to achieve accurate real-time positioning in the tunnel scene by combining the downlink time difference of arrival (DL-TDOA) with UWB technology. The DL-TDOA technology is based on Ultra Wide Band (UWB) data transmission technology, which can effectively reduce the interference of other electromagnetic waves and reduce the data transmission time. By calculating the transmission time of the wireless electromagnetic wave between the vehicle and the fixed base station, the technology can determine the real-time position of the vehicle and greatly reduce the time loss of data in transmission. DL-TDOA based on UWB technology has high precision, while DL-TDOA based on UWB technology has many advantages, such as high precision, strong anti-jamming ability, low power consumption and a high transmission rate which are suitable for accurate positioning and navigation in tunnel scenarios. In the final tunnel experiment, several tests were carried out at speeds of 30km/h, 60km/h and 80km/h respectively. By comparing the coordinate position after the conversion with the satellite coordinate, the real-time kinematics (RTK), it was concluded that the position error of vehicles in the tunnel is less than 1m, and the real-time positioning of vehicles in the tunnel is realized.

Keywords: RTLS, UWB, DL-TDOA, Tunnel positioning

1 Introduction

The intelligent transportation system [1] integrates some advanced science and technology which includes information processing technology, data communication technology [2], sensor technology [3], electronic control [4] technology and others, into transportation management, vehicle transformation, and service modes. This position technology combines the relationship between vehicles, roads and users. It aims to construct a safe, efficient, intelligent and green comprehensive transportation system. It provides traffic information network for users and goods transportation to pass through safely and rapidly. It provides a free and common communication transmission service for vehicle to vehicle or vehicle to road interaction, and it possesses a full-time emergency response service when emergencies occur. Thus, position technology plays a critical role in intelligent transportation.

The tunnel project plays an important role in improving the technology of highway, shortening the road distance, enhancing the transportation capacity and reducing accidents. Due to the shielding effect of tunnel on radio signals [5], satellite signals [6] cannot be used to detect the vehicle position in the tunnel. Therefore, the navigation and position function in tunnel has always been a difficult intelligent transportation situation in order to actively respond to the construction and development strategy of intelligent transportation, promote the intelligent road network management, vehicle road coordination and travel information service [7]. In the case of not increasing the complexity of information transmission [8] and the receiving terminal, a new solution is proposed to enhance the accuracy of real-time navigation in tunnels and provide higher navigation and positioning services in tunnels.

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In the closed tunnel environment, inertial navigation [9] is generally used for the positioning of high-speed vehicles. However, the high price and high cost of this technology is not suitable for the construction and implementation of large-scale projects, neither is it accurate enough. To solve the problem of precise positioning in this special scenario, indoor positioning technology should be relied on. The main positioning technologies include Bluetooth [10], Infrared, Radio Frequency Identification (RFID), ultrasonic [11], WiFi, and ultra-wideband (UWB) [12]. The traditional UWB technology [13] transmits data by sending and receiving very narrow pulses within a nanosecond or below. It causes serious time delay when it only employs six channels, which is not suitable for accurate positioning under high-speed driving or when there are multiple vehicles at the same time.

Based on traditional UWB technology [14], this paper proposes to combine the downlink time difference of arrival (DL-TDOA) to realize accurate positioning and navigate the high-speed vehicles in the tunnel. UWB can identify hidden objects or moving objects behind the wall with extremely weak synchronous pulses, and the positioning error is only one or two centimeters. That is to say, the same UWB equipment can realize three functions: communication, radar and positioning.

According to the time difference of the radio signal propagation between the location label and different base stations, the distance difference between the location label and the four groups of positioning base stations is calculated. DL-TDOA just needs location tags to transmit or receive signals, so it can achieve a higher positioning dynamic and positioning capacity without any capacity limitation, and can realize dynamic return.

DL-TDOA is a new downlink broadcast UWB technology, which is based on the calculation method of positioning by time difference. The distance to the source is further determined by measuring the time the signal arrives at the base station. Its advantage lies in that DL-TDOA has no signal coupling problem, like the traditional way of direction finding by phase to calculate the azimuth angle. Due to the phase measuring the cycle of 2π being uncertain, the general method of using an antenna baseline is smaller than the wavelength of the signal to avoid the rewinding 2π period. However, the wavelength of high-frequency signals is relatively short, which makes the distance between test antennae relatively close, and it is easy to generate signal coupling resulting in measurement error. DL-TDOA detection only requires one antenna, there is no phase fuzzy problem, and because the direction finding baseline can be uncontrolled, it is solved at the source of signal coupling. The complexity of DL-TDOA is low, and for a TDOA monitoring station, the requirement for antenna is not high. Moreover, the detection antenna and receiver only need to be configured, even though different antennae are used in different monitoring stations. The direction finding antenna itself is an antenna array composed of a group of antennae, and each antenna in the array should be kept consistently as far as possible to reduce the impact on the accuracy of direction finding. This would raise the cost of the system and is not applicable to large-scale monitoring. After DL-TDOA is optimized by the optimization algorithm, the calculation error of detection is in the order of 100ns. For the DL-TDOA monitoring station, the accuracy of time measurement determines its positioning accuracy. In order to verify the accuracy of DL-TDOA, this paper adopts a real-time kinematics (RTK) [15] system to measure the real vehicle trajectory.

From the technical point of view, the combination technology based on GPS, DL -TDOA and visual positioning is one of the most ideal precise positioning and navigation technologies under high-speed driving, whether from the perspective of positioning accuracy, safety, anti-interference, power consumption, etc.

This paper is structured as follows Section 2 introduces the related work of indoor positioning. In Section 3 the system structure of DL-TDOA is described, including how to convert and process data. Section 4 introduces the experimental related scenario analysis and equipment devices reference data, and carries on the performance analysis to the DL-TDOA technology and the reference technology RTK. Section 5 is the summary of the whole system.

2 Related Work

Some outdoor positioning technologies, such as GPS, BeiDou Navigation Satellite System [16], inertial navigation, ground base station, already provide stable navigation and positioning services. These technologies combining with RTK technology [17] are applied to outdoor vehicle navigation, automatic driving, and other fields. However, some studies indicate that above high-accuracy positioning navigation can’t be used for high-speed driving and a closed environment, for example, the tunnels. Inertial navigation is expensive for the construction and implementation of large projects. Although these technologies might not be suitable for real-time positioning, they still contribute a lot to building a smart city. Therefore, this paper analyzes some most common and popular indoor positioning technologies and gives the current best solution to real-time high-speed tunnel positioning using different sensors and technologies.

The real-time high-accuracy positioning system includes a Real-Time Location System [18] and a Real-Time Location Services [19], which are the most advanced technologies of smart transportation. The Real-Time Location System uses sensor detecting technologies to obtain information of roads and vehicles. By utilizing advanced 5G technologies and the Internet of the new generation, the Real-Time Location System achieves the information interaction between vehicles to vehicles and vehicles to roads in real-time. At the same time, the Real-Time Location Services considers the information from roads and vehicles and combines them to go on vehicle safety control and road collaborative management. The Real-Time Location System and Real-Time Location Services can fully realize the effective coordination of people and vehicles, ensure traffic safety, and improve traffic efficiency, thus forming a safe, efficient and environmental protection road traffic system. In the vehicle-road cooperative system, the precise positioning of the vehicle is the core problem to realize vehicle cooperative control. At present, indoor positioning technology mainly includes Bluetooth, WiFi, RFID, ZigBee, UWB, infrared, ultrasonic, etc.

UWB is a low power, short distance wireless technology which can transmit large amounts of digital data over a wide spectrum of frequency bands. UWB has multiple reference points that are positioned in a vehicle or room, and are time-synchronized. UWB devices release high-frequency bursts and the signal is time-stamped when received. The timestamps from the different anchors are then calculated by the UWB gateway using multilateration algorithms based on TDOA to compute the approaching device's location. Apart from this, a UWB device also has the advantage of durable battery life which can last for several years due to its unique purpose. Ding et al. [20] proposed a method to improve the accuracy of the UWB system by compensating for errors. This method, which put together UWB transceiver DW1000, controlled by STM32, and Time of Flight (TOF) algorithm, realized improved accuracy at the end of the testing.

Boukour et al. [18] explored the possibility to utilize UWB as an indoor positioning system and realized the possibility since it works very well in masked environments such as tunnels as it can provide continuous localization from inside to outside, or outside to inside the system unlike the GPS or the GNSS systems. The paper evaluated two UWB methods and the Modified Gegenbauer function (MGF)-based positioning system, produced better results than the code division multiple access (DS-CDMA)-based positioning system. Leitinger et al. [21] presented a highly robust method of indoor positioning in which a synthesized framework that utilizes equivalent Fisher information by considering the bistatic transmission between infrastructure and the effect of clock offsets, the Cramér-Rao lower bound is obtained for multipath-assisted positioning. The paper concludes that applicability of the framework is realized in the localization of a specific environment.

Zigbee is a short-range, low speed, wireless network protocol with low cost and low power consumption suitable for industrial, building and home usage. Dong et al. [22] theoretically proposed a wireless ZigBee sensor network that would be used indoors in order to strengthen the signal of the satellite for the use of satellite positioning. This system would be based on a received signal strength indication (RSSI) model. The final RSSI range obtained is only suitable for some, not all environments. Liang et al. [23] proposed a ZigBee-based affordable smart home security system in order to reduce the number of thefts and home intrusions in Sarawak, India. The proposed method utilizes sensor nodes and transmits instantaneous data to the corresponding Android application. In the event of a security breach, the phone alarm is set off, warning the user. The system is highly secure and functional and is only limited by the phone battery life.

Alipio et al. [24] proposed the caching of data in Wireless Sensor Networks (WSNs) as a method to improve transport protocol functionality. This method effectively reduced interference from other wireless technologies including Bluetooth and Wi-Fi, thereby ensuring better optimized consumption of power and transmissions that are more reliable from end-to-end. Some WSN applications include smart traffic monitoring, by collection of instantaneous multimedia data including vehicle license plates and the number of vehicles, and smart environment monitoring where the collected data would be compiled to useful information such as global warming updates.

Downlink time difference of arrival (DL-TDOA) is the second most popular spacecraft transmission receiver and depends on the time and speed that a signal arrives rather than the time the signal was sent. In light of this, Peral-Rosado et al. [25] proposed a physical-layer abstraction system in urban macro-cell (UMA) environments that makes an assessment of the abilities of GNSS and 5G DL-TDOA. This hybridization serves as a vital solution to the realization of high-accuracy positioning systems, and this includes self-driving vehicles. The proposed method realizes 95% accuracy for all cases below 5m which is very significant with room for improvement. Instead of utilizing the traditional five sensors required to determine the precise 3d position, Díez-González et al. [26] proposed a four-beacon TDOA method to solve 3d problems. The distance between solutions in the problem permitted the transformation of the problem into an analogous one, thereby achieving genetic algorithms to obtain optimized sensor distribution with more receivers. This paper achieved 96.7% accuracy in cases where vehicles travelled at speeds less than 25m/s. In earlier years, Yu et al. [27] simulated a proposed moving source localization system which combined TDOA (time difference of arrival) and FDOA (frequency difference of arrival). The paper concluded, from the obtained results, that the proposed method achieved better performance than the two-step weighted least squares (WLS) approach. This attained the Cramér-Rao lower bound (CRLB) at a sufficiently high noise level before the threshold effect occurred.

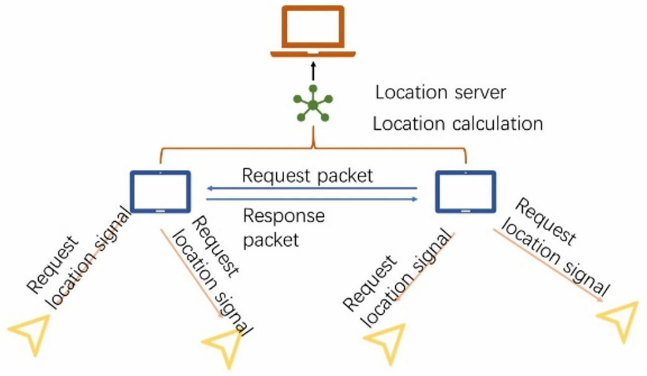
3 DL-TDOA-based RTLS Technology

The traditional UWB technology mainly adopts extremely short pulse signals to transmit data which guarantee high-speed communication with very small transmitting power. UWB technology is an improvement on traditional communications technology to transmit data by sending and receiving extremely narrow pulses of a nanosecond or less. Because of the advantages of low power consumption, strong anti-jamming ability, high security, low system complexity, it can be applied to indoor object positioning and tracking and can provide very precise positioning accuracy. UWB mainly uses very short pulse signals to transmit data, which guarantees high-speed communication while transmitting with very little power. UWB technology is a new communication technology which is very different from traditional communication technology. Instead of using the carriers of traditional communication systems, it transmits data by sending and receiving extremely narrow pulses of nanosecond or less, thus having a bandwidth on the GHz scale. Therefore, the characteristics of UWB system are suitable for use in high-speed mobile environment.

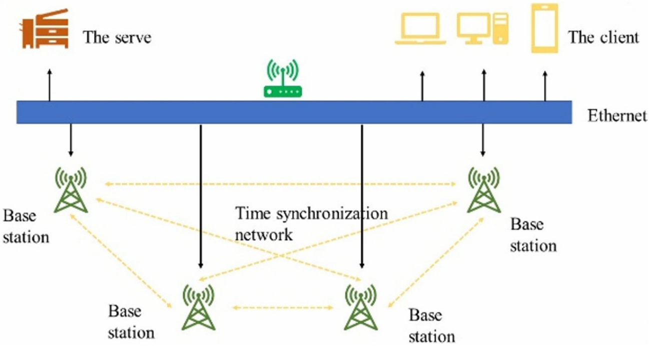
The traditional UWB technology adopts the uplink-request mode and only has 6 channels, which will cause time delay. Therefore, it is neither suitable for accurate positioning under high speed driving nor for common accurate positioning under the action of multiple vehicles. Using UWB technology, the time difference of radio signal propagation between the positioning tag and two different positioning base stations is measured, and the distance difference between the positioning tag and four groups of positioning base stations is obtained. DL-TDOA technology does not require reciprocating communication between the positioning tag and the positioning base station, but only requires the positioning tag to transmit or receive signals only, so it can achieve higher positioning dynamic and positioning capacity, and is not limited by any capacity, and can realize dynamic transmission back.

DL-TDOA adopts downlink broadcast propagation technology on the basis of traditional UWB. It is a way of positioning by using time difference, and the distance of signal source is determined by the arrival time of signal sent to the base station by the label. The advantages of this approach are that it can avoid the signal coupling problem due to the traditional way of direction finding by phase difference to calculate the direction angle. In the measurement of phase of uncertainty, there are two Π cycles and the DL-TDOA monitoring station only needs one, thereby fundamentally solving the problem of signal coupling directly. Secondly, after the optimization algorithm, the calculation error of the DL-TDOA time difference is on the order of 100 nanoseconds, which is about 30m in terms of the accuracy of positioning.

The principle of DL-TDOA is to obtain the time difference of the radio signal propagation between the positioning tag and different positioning base stations by using the signal propagation technology of UWB, and then obtain the distance difference between the positioning tag and four groups of positioning base stations, thus obtaining the real-time position of the vehicle. As shown in Figure 1(a) and Figure 1(b) DL-TDOA reduces the time wasted in the round trip communication of the signal as it only receives the signal from the location tag, and the base station in the tunnel forms a dynamic LAN + and is not limited by any capacity. The transmission layer is divided into the wireless transmission network and the wired transmission network. The wireless transmission network provides the data transmission link for the positioning base station through the WiFi channel, the wired transmission network provides the data transmission link for the positioning base station through the wired Ethernet (such as POE) mode, and the wired transmission network also provides the data transmission link for the wireless transmission network.



(a) Traditional UWB positioning technology



(b) DL-TDOA positioning technology

Figure 1. The frameworks of traditional UWB and DL-TDOA

In DL-TDOA, edge detection is used in the sensor to reduce the pressure of server calculation because, in UWB, the router uploads the time difference information between the vehicle and the base station to the server and then the server calculates the location information of the vehicle since uploading the location label to the server will consume the upload time. When the vehicle needs vehicle information in the tunnel, the location tag then downloads the location information calculated by the server, which will consume the download time. Due to the time disguise of uploading data and downloading data, the real-time positioning of vehicles cannot be achieved. DL-TDOA inherits the strong anti-interference ability of traditional UWB and is insensitive to signal attenuation. Especially in the closed environment with numerous vehicles in the tunnel, UWB will not interfere with other equipment and other advantages. An edge detection algorithm is added into the sensor to calculate the position relationship between anchor points and vehicles. The sensor uploads and downloads location information to the bridge node at a frequency of 4 Hz. Then, unlike UWB, routers and servers are only used to transmit and store data and servers are not involved in calculating any location information. In DL-TDOA, the work of calculating the position of the vehicle is assigned to the vehicle itself. After the vehicle calculates the position, it only needs to upload it to one bridge node, while there are multiple bridge nodes in UWB.

At the same time, DL-TDOA can also upload the vehicle information to the server for further analysis of the vehicle by the application software. The uploading frequency of DL-TDOA is 1, 2, and 4Hz. It is easily and flexibly configured according to requirements, and the computing power of USB edge reaches 26Hz. DL-TDOA’s anchor nodes automatically form an IPv6 mesh network based on infinite communication technology, which is flexible and scalable, so there is no upper limit to the number of vehicles that can be accommodated, compared to the traditional UWB, which is usually less than 300 vehicles. DL-TDOA adopts wireless connection between anchor nodes, which greatly reduces the construction cost. Therefore, the low cost and real-time DL-TDOA solves the problem of vehicle positioning delay in the tunnel caused by traditional UWB.

Figure 2 below shows the architecture of the proposed automated location solution using DL-TDOA, which includes the following components: different information labels on the vehicle, anchor or bridge nodes, switches, routers, networks and RTLS servers. This vehicle positioning system is positioned in the tunnel which is the area of testing. Figure 2 also shows the common vehicle tags and these include the sensor tag, badge tag, asset tag and a positioning unit. Independently, each tag computes data based on the DL-TDOA algorithm and can calculate the position information. The anchor nodes automatically form an IPv6 mesh network based on wireless communication technology which has very flexible scalability. POE power is the only requirement for each anchor node and approximately 15% of them are required to be connected to switches in order to connect to the data network. The positioning module can seamlessly transmit sensor data to the cloud by accessing the serial port and sensor interface. In addition to the time stamp, the perceived data receives a position stamp, with which to realize the Internet of Things platform with location.

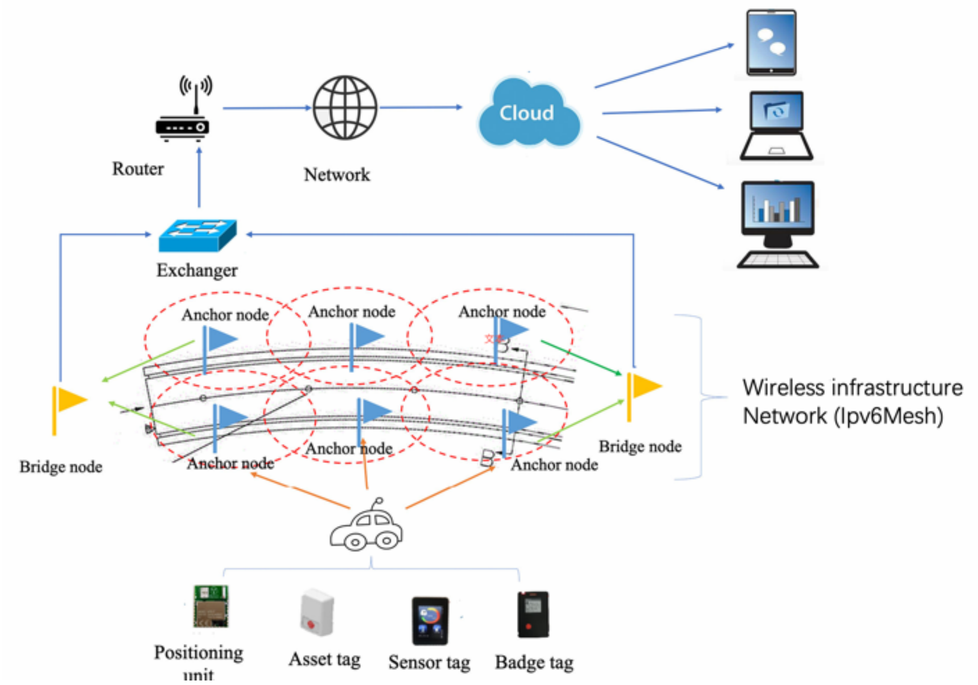


Figure 2. The architecture of the proposed automated location solution using DL-TDOA

The mathematical formula shows that the distance between a moving point and two fixed points is a hyperbola. Since the vehicle is a three-dimensional coordinate in the tunnel, at least four observation stations are needed to determine the position of the vehicle at a point. The principle of TDOA positioning is to use the time difference between the signals received by multiple base stations to determine the location of labels. According to the mathematical relationship, the distance difference to the known two points is constant, that is to say, the time difference between the tag sending signals to the two base stations is constant, and the position of the tag must be on the hyperbola with the two points as the focus. Then there are four known points (four positioning base stations) and there will be four hyperbolas. The intersection of the four hyperbolas at one point is the location of the UWB positioning tag.

The specific principle is shown in Figure 3 and Figure 4. The specific algorithm of TDOA is as follows: assumed that the time when the Nth base station receives the UWB signal from the label is T_i (i = 0, 1, 2, 3, …), and suppose the distance from the tag to the Nth base station is R_i (i = 0, 1, 2, 3, …),

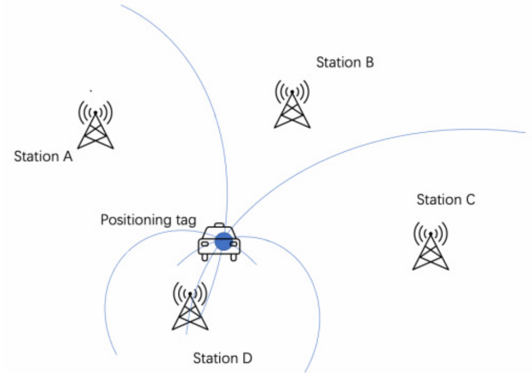


Figure 3. Signal transmission of four base stations

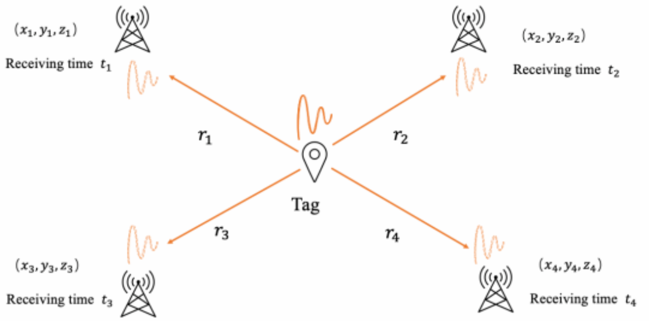


Figure 4. The utilized positioning principle

Assuming that the coordinate of the target vehicle is (x, y, z), there are at least $M+1$ anchor nodes in the DL-TDOA inside the tunnel. The main station is set as S_0, the remaining substations are set as S_i (i = 0, 1, 2, 3, …), and its coordinates are set as (X_i, Y_i, Z_i), (I = 0, 1, 2, 3, …, M). Set the time of the target vehicle to each substation as t_i, (i = 0, 1, 2, 3, …, M). The difference between the arrival time of each substation and the arrival time of the main station is π_i, (i = 0, 1, 2, 3, …, M). The distance difference between the vehicle, the substation, and the terminal can be obtained by multiplying the arrival time difference by the speed of light: $\Delta\gamma_i = c\pi_i$ Since C represents the theoretical speed of light, $R$is a known quantity, and the distance difference can be obtained directly from the distance between the target vehicle and the main station and the substation.

By using the Pythagorean Theorem and the above equation, the unknown quantity R is eliminated simultaneously.

$$\begin{aligned} R = \Delta\gamma^2 + 2\gamma_i\gamma = 2[x(x_0 - x_i) + y(y_0 - y_i) + z(z_0 - z_i)] \\ + (x_i^2 + y_i^2 + z_i^2) - ({x_0}^2 + {y_0}^2 + {z_0}^2) \end{aligned} \tag{1}$$

Let $l^2 = (x_i^2 + y_i^2 + z_i^2)$ then,

$$\begin{aligned} \Delta\gamma_i^2 + 2\Delta\gamma_i\gamma = 2[x(x_0 - x_i) + y(y_0 - y_i) + z(z_0 - z_i)] \\ + l_i^2 - l_0^2 \end{aligned} \tag{2}$$

The results:

$$\Delta\gamma_i^2 + \frac{\Delta\gamma_i^2 - l_i^2 + l_0^2}{1} = x(x_0 - x_i) + y(y_0 - y_i) + z(z_0 - z_i) \tag{3}$$

i represents the number of anchor nodes, x, y, z are the unknown numbers, so the above equation is rewritten as the following matrix:

$$\begin{bmatrix} x_0 - x_1 & y_0 - y_1 & z_0 - z_1 \\ \vdots & \vdots & \vdots \\ x_0 - x_m & y_0 - y_m & z_0 - z_m \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ x \end{bmatrix} = \begin{bmatrix} \Delta\gamma_1 \\ \vdots \\ \Delta\gamma_m \end{bmatrix} = \gamma_0 + \begin{bmatrix} \dfrac{\Delta\gamma_1^2 - l_1^2 + l_0^2}{2} \\ \vdots \\ \dfrac{\Delta\gamma_1^2 - l_1^2 + l_0^2}{2} \end{bmatrix} \tag{4}$$

The matrix of formula (4) can be divided into:

$$A = \begin{bmatrix} x_0 - x_1 & y_0 - y_1 & z_0 - z_1 \\ \vdots & \vdots & \vdots \\ x_0 - x_m & y_0 - y_m & z_0 - z_m \end{bmatrix} \tag{5}$$

$$B = Cr + D = \begin{bmatrix} \Delta\gamma_1 \\ \vdots \\ \Delta\gamma_m \end{bmatrix} \gamma_0 + \begin{bmatrix} \dfrac{\Delta\gamma_1^2 - l_1^2 + l_0^2}{2} \\ \vdots \\ \dfrac{\Delta\gamma_1^2 - l_1^2 + l_0^2}{2} \end{bmatrix} \tag{6}$$

According to the linear properties of linear equations, the solution set of $AX = B$ is the sum of the solution sets of $AX = Cr_0$ and $AX = D$. When $m = 3$, A is a square matrix. According to Cramer rule, its solution can be expressed as:

$$x_{ij} = \frac{|A_j|}{|A|} \tag{7}$$

Where A_{ij} is the determinant obtained by replacing the column element in a with a constant term. The new equation can be obtained:

$$\begin{cases} x = a_1\lambda + b_1 \\ y = a_2\lambda + b_2 \\ z = a_3\lambda + b_3 \end{cases} \tag{8}$$

Where a_i is the solution set of $AX = C$ and b_i is the jth solution set of $AX = D$. Then replace the x, y, z variables of equation (8) with those in equation (9):

$$\gamma^2 = (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \tag{9}$$

Substitute in Equation (8) above, suppose

$$\begin{cases} \delta = (a_1{}^2 + a_2{}^2 + a_3{}^2) \\ \phi = (a_1b_1 + a_2b_2 + a_3b_3 - a_1x_0 - a_2y_0 - a_3z_0) \\ \mu = (x_0 - b_1)^2 + (y_0 - b_2)^2 + (z_0 - b_3)^2 \end{cases} \tag{10}$$

then the final equation is :

$$\gamma = \frac{-\phi \pm \sqrt{\phi^2 - 4\delta\mu}}{2\delta} \tag{11}$$

When γ has multiple solutions, the positioning result obtained is not unique, that is, the positioning is fuzzy. In this case, it is necessary to add observation stations to determine the position information. When r has a unique solution, it means that there is a unique target position that we're looking at. When r is no solution, it represents the uncertain position. When γ is determined, the (x, y, z) coordinates can be reversed. Through the positioning of the label installed on the vehicle, the edge of vehicle location is then calculated to reduce the pressure signal delay and calculation, and the DL-TDOA algorithm obtains the position of the information added to the label in order to obtain accurate positioning information. The coordinates of positions within a tunnel to longitude and latitude are converted.

RTK as a reference method, DL-TDOA and RTK need to be placed in the same coordinate system for comparison. RTK is a commonly used satellite positioning measurement method, which uses longitude and latitude coordinates, and the international format is degrees, minutes and seconds. Since RTK is based on geodetic coordinates to collect data, WGS-84 ellipsoid reference algorithm is needed to convert the data coordinate system from geodetic coordinate system to X, Y and Z plane coordinate system. During the transformation, the origin of the coordinate system does not coincide with the origin used in the measurement. So you have to transfer the two frames to the same origin. Since the uplink DL-TDOA frequency is not equal to the RTK upload frequency, the difference compensation method is needed to find the missing value to achieve the same frequency. Since RTK and DL-TDOA need to be installed on the vehicle but they cannot be superimposed, the physical position difference needs to be subtracted. Therefore, the distance between DL-TDOA and RTK in the vehicle was artificially subtracted, and then the two were converted to the same coordinate system for trajectory comparison.

The positioning of anchor points in the tunnel also needs to be converted to the same coordinate system. Under the same coordinate system, RTK and total station are used to carry out manual overlapping measurement of the origin several times. Several points with small errors are selected to calculate the rotation angle of the coordinate system. After many calculations, the transformation between the coordinate system of the total station and the longitude and latitude coordinates is integrated. The raw output data of UWB is not 10Hz. In order to obtain 10Hz coordinate data, the difference multiplication method is adopted to obtain data in 10Hz format. Then UWB coordinates (equivalent to the total station coordinate system) are converted into longitude and latitude by using the transformation relationship between UWB coordinates and the total station coordinate system.

4 Experiments and Analysis

The deployment scenario is shown as Figure 5. Base stations are spaced 35 meters apart and arranged in rectangles:

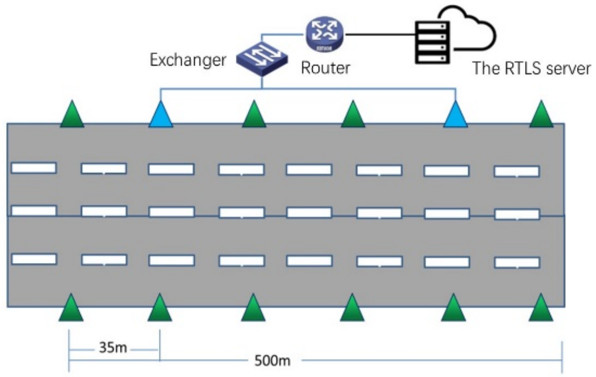


Figure 5. 500 tunnel reference deployment plan

After debugging the system, the broadcasting frequency of the system is 4 Hz, the label is set as the navigation mode, and the distance between the base stations is 35 meters apart arranged in rectangles. The procedure is as follows:

- Place the positioning label under the front windshield and fix it;
- Car drivers should patrol driving, driving in straight line for safety;
- Connect the V7 Universal Label through the serial line and connect to the computer;

- Use the serial port software PuTTY to receive the local output location of the label;
- Simultaneously record the moving track of the car through the camera;
- Export upload location data through server-side API;
- At the same time, connect the computer to grab the package tool and record the debugging information of the system;

For each test case, the following data information needs to be collected and compared:

- Serial port output 26 Hz position data;
- Server-side API to export location data;
- Motion track recorded by the camera;
- Position data measured by total station;

System information recorded by the packet capture tool. The computer is connected to the packet capture tool to record the system debugging information at the same time. For each test case, it needs to collect and compare the data information, including the 26Hz position data output by the serial port, the position data exported by the server-side API, the position data measured by the total station instrument and the system information recorded by the packet capture tool. The list of devices to set up is shown in the Table 1, the scene layout is shown in the Figure 5, the actual layout of the tunnel is shown in the Figure 6.

Table 1. Device list used in the test

No.	Device name	count
1	Bridge Node	2
2	Anchor Node	10
3	Location Server	1
4	PoE Exchanger	1
5	Router	1
6	Distance Meter	2
7	Total Station	1
8	Laptop	2
9	Network Cable	200m
10	V7 General Tag	4
11	PoE Extender	2

Figure 6. The tunnel scenario was established

The distance between RTK and DL-TDOA installed on the vehicle is 20cm, which leads to the deviation of the measurement results. It is necessary to manually subtract the position difference between the two vehicles. Besides, the signals sent by these two devices are not at the same frequency. Find the same location in the same frame.

By using RTK and total station to observe several points outside the tunnel, the transformation relationship between the two coordinates is calculated. The table shows the measurement results of 12 total stations. The table shows the measurement results of RTK as shown in the Table 2 and Table 3:

Table 2. Total station measurement results at 12 points

Dot No.	E	N	Z
0	0	0	0
RTK1	27.567	-15.917	0.129
RTK2	29.262	-4.919	-0.228
RTK3	130.25	32.44	-4.98
RTK4	75.742	9.37	-2.499
RTK5	-22.118	32.44	9.165
RTK6	-39.875	49.534	14.324
RTK7	-63.486	9.949	14.336
RTK8	-43.076	26.942	2.514
RTK9	-54.663	20.978	2.629
RTK10	-25.375	-4.658	1.148
RTK11	0.205	-43.497	-0.1
RTK12	10.899	-23.904	0.145

Table 3. RTK coordinates of 12 test points

Test point	latitude	longitude	Latitude (degree)	Longitude（degree）	Tool to convert right Angle X	Tool to convert right Angle Y
	4031.03679472	11554.37124139	40.51727991	115.90618736	4487542.477	407302.857
1	4031.0274701	11554.38911379	40.51712378	115.90648523	4487524.826	407327.8801
2	4031.03279325	11554.39183317	40.51721322	115.90653055	4487534.71	407331.8508
3	4031.04141048	11554.40877108	40.51735684	115.90681285	4487550.362	407355.9731
4	4031.03852650	11554.42599328	40.51730878	115.90709989	4487544.724	407380.2297
5	4031.05530439	11554.35674061	40.51758841	115.90594568	4487576.989	407282.7983
6	4031.06542828	11554.34607106	40.51775714	115.90576785	4487595.913	407267.9626
7	4031.04538044	11554.32697691	40.51742301	115.90544962	4487559.143	407240.5268
8	4031.05184495	11554.34380159	40.51753075	115.90573003	4487570.813	407264.4387
9	4031.05099153	11554.33379028	40.51751653	115.90556317	4487569.409	407250.2831
10	4031.03649243	11554.35155048	40.51727487	115.90585917	4487542.262	407275.0356
11	4031.01309343	11554.36972131	40.51688489	115.90616202	4487498.637	407300.1602
12	4031.02311336	11554.37720399	40.51705189	115.90628673	4487517.051	407310.9585

In Table 2 and Table 4, E represents the east and N represents the north. The space Cartesian coordinate system is established in the tunnel, which is the coordinate system of the vehicle under the total station. RTK technology is a real-time dynamic technology based on the carrier phase observation value. In the scene with satellite signals in a wide area, RTK technology obtains the centimeter-level positioning accuracy in a very short time, so it is used as the reference frame for positioning. The coordinate system corresponding to it is the coordinate system at the longitude and latitude as shown in Table 3. When measuring with the total station, a Gaussian projection plane coordinate system is adopted, so it is necessary to carry out a series of transformations of RTK coordinates to put the two coordinate systems in the same coordinate system, and then compare the vehicle tracks of RTK and DL-TDOA in the same coordinate system. The first step is to select a few points with small errors through multiple measurements of the selected origin position and the positions of the other two points. After multiple calculations, the origin is first overlapped and the other two points are used to synthesize the transformation relationship between the total station and the longitude and latitude coordinate system. Since the original output data of UWB in DL-TDOA is not 10Hz, in order to convert the frequency to 10Hz, the original data needs to be converted by difference and multiplication, so as to obtain the data in the format of 10Hz. By using the transformation relationship between the two coordinate systems, the coordinates of UWB (that is, the coordinates of the total station) and longitude and latitude are converted. So we can get the position of the vehicle in the same coordinate system. Figure 7 shows the relationship between RTK and total station at the origin of 12 manually measured points, and the difference distance after conversion. RTK2, RTK5, RTK6 and RTK7 are selected as the reference points. There are many reasons for relatively large errors, and the biggest influence is human factor, which depends on the experience of the surveyor.

Table 4. Comparison results of RTK and UWB measurements with the origin distance

Dot No.	E	N	Z	Total station	RTK	Phase difference distance (mm)
0	0	0	0			
RTK1	27.567	-15.917	0.129	31832.22232	30622.0392	-1210.183101
RTK2	29.262	-4.919	-0.228	29672.56654	30016.0130	343.4465378
RTK3	130.254	-4.938	-0.222	134232.8504	53698.2115	-80594.63883
RTK4	75.742	32.44	-4.98	76319.37804	77405.3166	1085.938576
RTK5	-22.118	9.37	-2.499	39655.23068	39918.0719	262.8412482
RTK6	-39.875	32.44	9.165	63589.56503	63820.5813	231.0263443
RTK7	-63.486	49.534	14.324	64260.83408	64520.0050	259.170969
RTK8	-43.079	9.949	14.336	50810.15258	47737.8464	3072.306128
RTK9	-54.663	26.942	2.514	58550.1499	59070.8927	520.7418112
RTK10	-25.375	20.978	2.629	25798.98426	27822.2127	2023.228475
RTK11	2.205	-4.658	1.148	43552.85334	43922.2598	639.4035148
RTK12	10.899	-43.497	-0.1	226271.4563	23385.0092	413.5529638

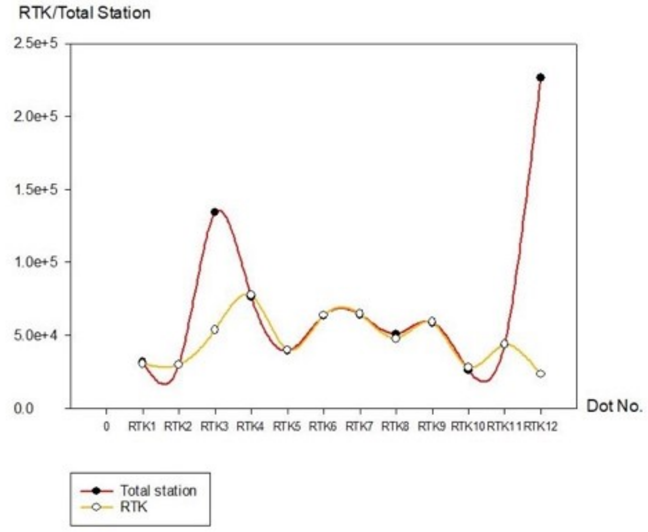


Figure 7. Error of RTK and total station

The Table 5, Table 6 and Table 7 show that vehicles are kept running at a uniform speed as far as possible in the tunnel. As shown in the Table 8, when the speed increases, the error of positioning accuracy will also increase, but the minimum error does not depend on the speed. As the velocity increases, the distance difference between the two points will increase correspondingly. But the error range is within the centimeter scale, which is acceptable.

Table 5. Error measurement for 30 km/h

Test Scenario	Maximum distance (mm)	Minimum distance (mm)	Mean distance (mm)
Test 1	1129	535	880
Test 2	1159	574	865
Test 3	1199	605	881

Table 6. Error measurement for 60 km/h

Test Scenario	Maximum distance (mm)	Minimum distance (mm)	Mean distance (mm)
Test 1	2116	1145	1600
Test 2	2190	1218	1637
Test 3	2110	1180	1657

Table 7. Error measurement for 80 km/h

Test Scenario	Maximum distance (mm)	Minimum distance (mm)	Mean distance (mm)
Test 1	3122	1306	2158
Test 2	3090	1188	2144
Test 3	3045	1221	2156

Table 8. Positioning test conclusion

Test scenarios	Positioning accuracy	Echolocation frequency
30km	30cm	4Hz,26Hz
60km	35cm	4Hz,26Hz
80km	40cm	4Hz,26Hz

5 Conclusions

In this paper, based on the traditional UWB, the technology of DL-TDOA is proposed to realize the real-time and accurate positioning of vehicles in the tunnel. DL-TDOA has achieved 100% signal coverage in the tunnel, and compared with the traditional UWB, the main advantage of DL-TDOA technology in tunnel positioning is low complexity, no need for redundant monitoring stations, high time efficiency and strong anti-interference ability. Without a cumbersome signal transmission process, DL-TDOA can realize large capacity, high security, flexible and scalable wireless communication network with simple equipment and distributed processing. At 4Hz and 250ms converted to 10Hz, the distance between every two points of the label is calculated every 100 seconds. The accuracy of DL-TDOA is less than 1 meter to judge whether the positioning is stable. After the conversion of RTK and UWB coordinates, the longitude and latitude coordinates of the vehicle are obtained by inverse calculation, so as to realize the real-time and accurate positioning of the vehicle under the condition of high-speed tunnel driving. In future studies, longer tunnels and more complex tunnel scenarios can be tested by DL-TDOA.

Author Contributions

Methodology, X. Y., L. S., X. W.; Project Administration, D. T.; Supervision, L. S.; Investigation, C. L. and X. Y.; Xiaofeng Yu is the corresponding author; All authors have read and agreed to the published version of the manuscript.

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