A Review of Research on Communication and Positioning Techniques for Vehicular Networks

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Abstract. This paper explores the advancements in communication and positioning technologies essential to vehicular communication systems, which are a cornerstone of autonomous driving. Firstly, key communication technologies like millimetre-wave and light detection and ranging (LIDAR) are analysed, with an emphasis on their roles in vehicle-to-vehicle (V2V) networks for enhancing safety and efficiency. Then, positioning systems like GNSS and RTK are examined in depth, emphasizing their potential for achieving high-accuracy localization under dynamic conditions. By systematically analyzing the strengths and limitations of these technologies, critical challenges including environmental factors, signal reliability, and cost constraints are identified. At the same time, potential solutions such as sensor fusion and algorithmic optimization are proposed. This comprehensive analysis provides valuable insights for researchers and practitioners aiming to advance the development of intelligent transportation systems and autonomous vehicle networks.

Keywords: Vehicular communication systems, V2V communication, GNSS, RTK.

1. Introduction

In recent years, there has been a notable interest from both academic and industrial sectors in the development of automated driving. This technology has the potential to free drivers from the physical and mental constraints, while also enhancing traffic safety and energy efficiency, and optimizing the utilization of public resources [1]. The efficient and reliable vehicular networkis crucial to autonomous driving technology, which enables real-time perception, decision-making, and control of vehicles and the road environment. Therefore, on the study of the vehicular networks is of great value.

The vehicular network refers to systems that facilitate information exchange between vehicles (V2V), vehicles to infrastructure (V2I), vehicles to pedestrians (V2P), and vehicles to networks (V2N) [2]. The aim of the vehicular network is to enhance traffic efficiency and safety through coordinated communication. The core of this system lies in constructing a highly dynamic network using various communication methods to ensure that different types of information can be transmitted promptly and effectively. The vehicular network is an indispensable part of intelligent transportation systems (ITS), supporting various application scenarios such as autonomous driving, road information sharing, and traffic congestion management.

In the field of vehicular networks, the communication and positioning technology serve as the basis for the exchange of digital data and the accurate location determination of vehicles. In more specific, the concept of vehicle-to-everything (V2X) communication has emerged as a pivotal technique in the realm of autonomous driving [3]. As a key technology enabling the transformative potential of autonomous driving, V2X significantly improves traffic safety, congestion management, and energy efficiency.

The objective of this review is to provide a comprehensive and systematic overview of the advancements in communication and positioning technologies within vehicular networks. It aims to analyse the strengths and limitations of existing research, while also identifying potential avenues for future research. This will serve as a valuable reference for researchers engaged in related fields.

2. Vehicular Communication Technology

The following section of this paper will introduce and summarise the existing research on vehicular networks. It will cover the definitions of various technologies, their research focus, real-world applications, and a comparative analysis of their strengths and weaknesses. In the context of vehicular communication, V2X technology plays a pivotal role and includes various communication modes. V2V denotes communication between vehicles within a vehicular network, facilitating the exchange of information such as speed, position, and driving direction, with the objective of enhancing driving safety. The technologies employed in this context include, but are not limited to, millimetre-wave and LIDAR. This section will describe the specific models and common use cases of these two technologies, before concluding with a comparison of their respective advantages and disadvantages.

2.1. Millimetre-wave Technology

Millimetre-wave technology employs electromagnetic waves with wavelengths spanning a range of one to ten millimetres, corresponding to frequencies between 30 GHz and 300 GHz. Positioned between the microwave and infrared spectra, millimetre waves are characterized by high frequency and high bandwidth, rendering them suitable for large-capacity, high-speed wireless communication. To gain a comprehensive understanding of electromagnetic generation, propagation, and the interactions of charge and current, it is essential to utilise the fundamental principles outlined in Maxwell's equations. The System of equations of Maxwell are shown in (1).

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0}, \nabla \cdot B = 0, \nabla \times E = -\frac{\partial B}{\partial t}, \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \tag{1}$$

where E is the electric field strength, ρ is the electric charge density, ε_0 is the vacuum permitivity, B is the magnetic induction strength, J is the current density, and μ_0 is the vacuum permeability.

Millimetre waves, being high frequency electromagnetic waves, follow the same fluctuation equation shown in (2).

$$\nabla^2 E - \mu\varepsilon \frac{\partial^2 E}{\partial t^2} = 0 \tag{2}$$

In practical applications, millimetre-wave technology offers several advantages. Its short wavelength allows for smaller antenna sizes, which facilitates array design, and it provides access to underutilised frequency spectrum resources, given that lower-frequency spectrum resources are limited. However, millimetre waves are susceptible to absorption, reflection, and scattering during atmospheric propagation, which results in a limited transmission range.

Nevertheless, the constraints of this technology must be acknowledged. The relatively advanced nature of millimetre-wave technology necessitates the development of highly complex radio frequency (RF) and antenna designs, which in turn gives rise to elevated costs of both development and manufacturing. This, in turn, presents a significant challenge to the adoption of this technology on a widespread basis. Furthermore, millimetre-wave communication necessitates beamforming to facilitate directional signal transmission, thereby requiring precise alignment between the transmitting and receiving antennas. Any discrepancy in alignment can result in a notable reduction in signal strength. In V2V scenarios, where the positional relationship between vehicles is in a state of constant flux, the ability to make precise real-time position predictions and provide feedback is of paramount importance for maintaining stable signal transmission. In circumstances where data transmission is taking place between multiple vehicles moving at high speeds in irregular patterns, the efficiency of signal transmission may be adversely affected.

2.2. LIDAR Technology

LIDAR technology is a remote sensing technique that determines the distance and spatial position of an object by emitting laser pulses at the target and measuring the time of flight (TOF) of the reflected signal. By combining positional and angular information, LIDAR generates a three-dimensional point cloud, which represents the surface morphology of the target object. Moreover, the intensity of the reflected signal received by the detector is influenced by factors such as the material, angle, and distance of the target object. This allows for the calculation of specific characteristics of the object. In vehicle-to-vehicle (V2V) communication, the utilisation of millimetre-wave and LIDAR technologies is employed for the purpose of perceiving the surrounding environment of the vehicle in question. This may include the detection of the distance, speed, and azimuth angle of preceding or oncoming vehicles. Furthermore, the Doppler effect, which is caused by the relative velocity of the target, results in a frequency shift in the received signal compared to the transmitted signal, thus enabling the speed of the preceding vehicle to be detected. The relative speed can be calculated by employing a two-dimensional Fast Fourier Transform (FFT) to quantify the frequency shift.

Besides, for detecting the azimuth angle of the preceding vehicle, it is necessary to use an antenna array and measure either the time of arrival or the phase difference of the signal. If using a phase difference algorithm, assume that the radar has two receiving antennas spaced at a distance of d_a. When the target signal arrives from direction θ, the path difference between the two antennas is $\Delta d = d_a sin\theta$, resulting in a phase difference of $\Delta\phi$. The formula is shown in (3).

$$\theta = \arcsin\left(\frac{\Delta\phi \cdot \lambda}{2\pi \cdot d_a}\right) \quad (3)$$

The combination of millimetre-wave and LIDAR technologies in V2V communication allows for the full exploitation of their respective advantages. To illustrate, millimetre-wave technology provides the capacity for long-range dynamic target detection, whereas LIDAR offers high-precision perception of static environmental details. Furthermore, millimetre-wave communication can facilitate the rapid transmission of data sensed by LIDAR, thereby enhancing the reliability of V2V information sharing.

In contrast, LIDAR technology is highly susceptible to environmental factors. For example, in meteorological conditions characterized by precipitation, such as rain, snow or fog, particles such as water droplets have the potential to scatter and absorb laser signals, which may result in a reduction in detection range or an increase in measurement errors. In high-intensity lighting environments, the laser receiver may experience interference. Furthermore, LIDAR performs poorly in detecting low-reflectivity targets, such as black objects or materials that absorb light. This is due to the fact that the surface of these objects absorbs the emitted laser, resulting in no or weak reflected signals received by the detector. This can lead to reduced measurement accuracy or even missed detections of certain targets.

Based on the characteristics, LIDAR has a wide range of application scenarios. For instance, sensor fusion through loosely coupled GNSS-RTK and LIDAR can achieve precise positioning. By integrating sensor data with a Kalman filter, particularly when incorporating LIDAR, the drift caused by GNSS signal loss can be effectively mitigated, improving positioning accuracy in GNSS-limited environments [4]. Another study proposed a multi-sensor fusion vehicle positioning system designed for complex urban environments. This system combines the strengths of GNSS and LiDAR, enhancing robustness in rapidly changing environments and achieving a positioning accuracy of 5-10 centimetres root mean square error (RMSE) [5].

3. Positioning Technology

Regarding vehicular positioning technology, Global Navigation Satellite System (GNSS) and Real-Time Kinematic (RTK) are inextricably linked with V2X and other autonomous driving technologies. The distinctive features of these two positioning technologies, such as extensive coverage and high accuracy, provide a robust foundation for lane-level positioning in autonomous driving. This discussion will elucidate the fundamental principles of both technologies, including their definitions, specific applications, and scenarios, and will finally compare their advantages and disadvantages in different use cases.

3.1. GNSS

GNSS employ satellite signals for the purpose of achieving precise global positioning. The term refers to the collective of satellite systems that have been independently developed by multiple countries and regions across the globe. Despite the diversity of these systems, they operate on similar positioning principles.

In the context of vehicular applications, the GNSS receiver on board is designed to receive signals from a minimum of four satellites. The satellites transmit data regarding their respective positions and time on fixed frequency bands, specifically the L1 band at 1575.42 MHz and the L2 band at 1227.60 MHz. The time delay of the signals received is used to calculate the distance to each satellite, and the user's position is determined by trilateration, including the latitude, longitude, and altitude. Of these satellite systems, the Global Positioning System (GPS) is the most well-known. It consists of 31 active satellites distributed across six orbital planes at an altitude of approximately 20,200 km, with an inclination of 55 degrees. The orbital period of each satellite is approximately 12 hours. The primary control station, situated in Colorado, USA, in conjunction with backup control stations and worldwide monitoring stations, bears the responsibility of continuously monitoring satellite status and performing functions such as orbit adjustments and time synchronization. For vehicular terminals, the primary objective is to mitigate signal delays and interference caused by atmospheric propagation and other factors. The potential for error arises from a number of sources, including the impact of tropospheric and ionospheric conditions on signal speed, minor discrepancies in satellite positioning, and the inherent limitations of the receiver's signal processing capabilities. In environments characterized by the presence of significant obstructions, signals may be reflected, resulting in the potential for interference in the final positioning result.

A study has conducted a detailed analysis of four GNSS integrated navigation modes: loosely coupled, semi-tightly coupled, tightly coupled, and ultra-tightly coupled, highlighting their respective advantages and disadvantages. Among these modes, the loosely coupled approach offers the lowest robustness but is straightforward to implement, while the ultra-tightly coupled mode can achieve navigation even in extremely weak signal environments, albeit with significant system complexity.

Looking ahead, signal obstruction in urban environments remains a major challenge. There is a need to explore cost-effective, high-precision sensor fusion methods and to experiment with applying artificial intelligence models to optimize integrated algorithms [6].

As global navigation satellite system (GNSS) technology continues to evolve, major GNSS systems around the world are making strides in interoperability, as evidenced by the growing compatibility between Bidou and GPS. Regarding the current development of GNSS, particularly with considerations for data security and reliability, one study proposed a supervised machine learning-based method for detecting GNSS spoofing signals. Addressing the limitations of existing spoofing detection methods, the study analysed both laboratory and real-world data to measure spoofing signals and discussed the key variables critical to detection [7].

3.2. RTK

RTK builds upon the principles of GNSS by utilising fixed ground-based stations that receive signals, process them, and subsequently transmit corrections back to vehicles, thereby achieving centimetre-level accuracy. Ground-based stations, which are installed at known fixed positions, receive GNSS signals and calculate any errors that may occur in real time. Subsequently, the correction data are transmitted via a network to the mobile terminals (e.g. vehicles). The mobile terminal combines the received GNSS signals with differential data in order to achieve real-time positioning with a precision of one centimetre or less.

RTK has particular advantages in specific domains, notably in the context of autonomous driving. The positioning accuracy of RTK typically falls within 1-2 cm, with minimal latency, rendering it an optimal choice for precise positioning in dynamic environments. The corrections provided by ground stations effectively eliminate errors caused by atmospheric and satellite factors. Nevertheless, RTK is not without its own set of limitations. These include the substantial financial and temporal costs associated with the construction of a large number of ground stations, as well as the dependency on base station data transmission, which is typically effective only within a 50 km radius. In mountainous regions or urban environments characterized by a high density of tall buildings, the transmission of differential signals may become unstable due to signal reflection.

For RTK, which provides higher precision but is more restricted in its application scenarios, integrating the rapidly developing 5G network technology reduces the delay in transmitting differential signals, thereby further enabling high-precision positioning. Regarding the current applications of RTK, two studies have focused on advancements at the system and algorithmic levels. One study developed an autonomous mobile monitoring system based on RTK. This system integrates network-based RTK-GPS navigation, real-time environmental mapping, and intersection recognition to ensure accurate navigation even under limited satellite signal conditions. The study's results demonstrate that the vehicle can successfully complete tasks under adverse conditions, such as poor satellite geometry or GPS signal interruptions.

Another study focused on developing RTK-based speed control and path tracking algorithms for autonomous driving control. Unlike efforts aimed at enhancing positioning performance in various environments, this research adopted a novel approach by combining robotic driving and algorithmic control. It achieved sub-10-centimeter root mean square error (RMSE) accuracy without requiring additional sensors or complex vehicle dynamics models. However, under certain nonlinear motion conditions, the error remained relatively high. [8, 9]

4. Conclusion

The advancements in vehicular communication and positioning technologies underscore their critical role in enabling vehicular networks by integrating innovative communication methods like millimetre-wave and LiDAR, alongside precise positioning technologies such as GNSS and RTK, vehicular networks are increasingly capable of addressing complex operational challenges. However, limitations remain, including environmental susceptibility, system complexity, and cost barriers, which necessitate ongoing research. Future endeavours should focus on optimizing sensor fusion methodologies, enhancing signal robustness in urban environments, and leveraging emerging technologies like machine learning to refine system reliability. These efforts will not only improve traffic safety and efficiency but also lay a solid foundation for intelligent transportation systems. Through sustained interdisciplinary research, the promise of autonomous driving as a transformative technology for society can be fully realized.

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