Controller with Vehicular Communication Design for Vehicular Platoon System

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I would like to dedicate this thesis to my family.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

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Publications

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Abstract

Tracked Electric Vehicles (TEV) which is a new mass-transport system. It aims to provide a safe, efficient and coordinated traffic system. In TEV, the inter-vehicular distance is reduced to only a quarter of the regular car length and where drive at 200km/h enabling mass transport at uniform speed. Under this requirement, the design of the controller is particularly important. This thesis first developed an innovative approach using adaptive Proportion, integral and derivation (PID) controller using fuzzy logic theory to keep variable time-gap between dynamic cars for platooning system with communication delay. The simulation results presented show a significant improvement in keeping time-gap variable between the cars enabling a safe and efficient flow of the platooning system. Secondly, this thesis investigates the use of Slide Mode Control (SMC) for TEV. It studies different V2V communication topology structures using graph theory and proposes a novel SMC design with and without global dynamic information. The Lyapunov candidate function was chosen to study the impact which forms an integral part for current and future research. The simulation results show that this novel SMC has a tolerance ability for communication delay. In order to present the real time TEV platoon system, a similar PI controller has been utilized in a novel automated vehicle, based on Raspberry Pi, multi-sensors and the designed Remote Control (RC) car. Thirdly, in order to obtain precise positioning information for vehicles in platoon system, this thesis describes Inertial Measurement Unit (IMU)/Global Navigation Satellite System (GNSS) data fusion to achieve a highly precise positioning solution. The results show that the following vehicles can reach the same velocity and acceleration as the leading vehicle in 5 seconds and the spacing error is less than 0.1m. The practical results are in line with those from the simulated experiment.

List of Abbreviations

ACC	Adaptive Cruise Control
AI	Artificial Intelligence
AICC	Autonomous Intelligent Cruise Control
BD	Bidirectional
BDL	Bidirectional-lead Following
BPLF	Bidirectional Predecessor-lead Following
CACC	Cooperative Adaptive Cruise Control
CD	Constant Distance
COCAIN	Cooperative Optimized Channel Access for Inter-vehicle Communication
CTH	Constant Time Headway
DC	Distributed Controller
DSRC	Dedicated Short Range Communication
EV	Electric Vehicle
FG	Formation Geometry
GPIO	General-purpose Input/Output
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
HTS	Highway Transportation System
IFT	Information Flow Topology
IMU	Inertial Measurement Unit
INS	Inertial Navigation Sensor
ITS	Intelligent Transport Systems

I2C	Inter-integrated Circuit
KF	Kalman Filter
LAM	Leader Adjacency Matrix
LF	Lyapunov Function
LV	Lead Vehicle
ND	Node Dynamic
NLD	Nonlinear Distance
OBU	On Board Unit
PF	Predecessor Following
PID	Proportion Integral and Derivation
PLF	Predecessor-leader Following
PNT	Position Navigation and Timing
RC	Remote System
RTK	Real Time Kinematic
SMC	Slide Mode Control
TELCO	Telecommunication Network for Cooperative Driving
TEV	Tracked Electric Vehicles
TPLF	Two-predecessor-leader Following
TPF	Two-Predecessor Following
T-S Fuzzy	Takagi-Sugeno Fuzzy
USRP	Universal Software Radio Peripheral
UD	Unidirectional
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WiMAX	Worldwide Interoperability for Microwave Access
4G	The 4th generation mobile networks
5G	The 5th generation mobile networks

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Chapter 1

Introduction

1.1 Vehicular platoon systems - an overview

1.1.1 Vehicle platoon introduction

In a vehicular platoon system (Fig.1.1), two or more vehicles are driving at a fixed distance apart. They can be interconnected through V2V or V2I communication technologies or both. The lead vehicle is the pilot vehicle, which has a set route and speed. The following vehicles automatically synchronize with the lead vehicle to perform the same deceleration operation, resulting in a faster reaction time compared to that of a human. The vehicles in a platoon system must rely on intelligent communication which involves both in-vehicle and out-of-vehicle systems.

Fig. 1.1 Vehicle platoon system

In-vehicle systems. In-vehicles require three sub-systems: sensors, controllers, and actuators. Sensors in the vehicle are the radars, lidars(light detection and ranging) or cameras that collect information such as vehicle speed and distance. The role of the controllers are to assist automated driving and help the driver making decisions which include adaptive cruise control, the pre-collision system, the engine control unit, the lane-departure warning system, the lane-keeping-assist system, the pre-crash system, and other advanced driver assistance systems.

Out-of-vehicle systems. For the Intelligent Transport System, V2I communication devices perform the exchange of data between vehicles and road infrastructure. V2I communication comprises hardware, software, and firmware and operates typically wireless and bidirectional. Infrastructure components, such as lane signs, road signs, and traffic lights, can wirelessly provide information to vehicles, and vice versa. The ability to quickly capture and share valuable, abundant data yields substantial security, mobility, and environmental benefits.

1.1.2 Advantages of vehicle platoon systems

- **Fuel economy** Vehicle platoon systems improve fuel economy. Driving in a close group allows a car to stay in the wake area of the preceding car, avoiding significant aerodynamic drag that is typical for a truck on the highway. The shorter the distance between the two cars, the smaller the aerodynamic drag. Research has shown that truck platooning on highways can reduce overall fuel consumption by roughly 7–14%.
- **Driver ease** A vehicle platoon is not fully driverless. However, the system assumes most of the work for the driver, reducing driver fatigue and the potential for an accident.
- **Safety** Platoon vehicles communicate with each other. The driving status of all the platoon vehicles can be constantly monitored. In an emergency, the braking action of the whole platoon can be very quick since the response time is fast.

1.1.3 Vehicle platoon progress

Studies have shown that the platooning of vehicles has a significant impact on the overall energy consumption [1], which opens up a new energy-saving strategy for road traffic. Existing energy-saving platoon research is mainly for heavy-duty trucks, using a high-speed close-range following strategy . Examples of conducted projects include: the European SCANIA project [2] and SARTRE project [3], the Japanese Energy-ITS project[4], the US PATH project [5], PlatoonPro project[6], Korean Hyundai platoon project [7], and the TEV project [8]. The following section will select a few of the most relevant projects.

PATH [5] The California Partners in Advance Transportation Technology (PATH) project have demonstrated Cooperative Adaptive Cruise Control with a three-truck platoon system on 14 September 2017, in which all three trucks had drivers. The following distance between trucks was 13.7 m to 15.2 m at 88.5 km/h – a 0.6 s gap. The drivers in the two following vehicles needed only their hands to steer while the system assumed the braking and accelerating.

Hyundai [7] Hyundai trucks platooned on the Yeoju Smart Highway using V2V communication to maintain 16.7 m between vehicles, which were limited to a constant speed of 60 km/h constant for safety. While the driver of the following truck had to steer, the autonomous technology controlled the accelerating, braking, and steering functions.

SARTRE [3] The Safe Road Trains for the Environment (SARTRE) project is being undertaken by seven European partners costing €6.4M. In January 2012, the SARTRE project went into the final phase with the demonstration of a three-car road train tested at Hällered proving ground in Sweden. The test vehicles followed a lead truck running autonomously at a speed of about 90 km/h. The gap between the platooning cars was approximately 6 m.

PlatoonPro [6] In PlatoonPro , two trucks are interconnected. The driver in the first vehicle steers, accelerates and brakes normally; the second truck, connected by a direct V2V link, has a human driver only for steering. The second truck's speed is controlled by that of the first truck, maintaining a relatively close following distance. Customer trucks have shown average fuel savings of over 7%, an annual savings of up to $10,000 per truck.

1.1.4 The TEV project

The TEV system (Fig.1.2[9]) is a fully automated highway system for Electric Vehicles (EVs) to achieve a zero-emission highway transportation system. The grid that feeds the dynamic road charging infrastructure provides enough power to propel the EVs in the single

Fig. 1.2 TEV lanes on the highway

TEV lane. EVs drive fully automatically where ten vehicles form one platoon and travel at 200km/h. The inter-vehicle spacing is only a quarter of a car length, reducing the overall aerodynamic drag coefficient of all ten cars. TEV claims the following benefits:

- **Safety plus.** No overtaking occurs the TEV lane, and the closed road system does not allow access to other cars. The restricted-access tracks with side barriers provide incomparable safety.
- **Energy savings and higher efficiency.** The TEV system has a large passenger capacity, equivalent to roughly 17 lanes of traditional highways. The TEV lane is straight, and the EVs drive at a steady speed. The grid supplies electrical power directly to the motor, which results in higher efficiencies. In addition, the small inter-vehicle spacing, reduces the aerodynamic drag, saving energy.
- **Less work for the driver.** In most vehicle platoons, the drivers' attention is required to steer. In the TEV system, there is no steering throughout the trip.

TEV aims to be the safest, fastest, and most versatile transport system possible with zero-emission EVs, rather than large trucks. TEV is a solution to improve passenger capacity, energy efficiency, and safety. Therefore, TEV has exceptional advantages over the other platoon vehicle options to meet the requirement of modern transportation.

1.2 One-dimensional network of dynamical systems

A vehicle platoon can be regarded as a special one-dimensional network dynamic structure. From the perspective of control, the vehicle platoon system can be viewed as a one-dimensional network dynamic system composed of multiple single vehicle nodes, which control individual vehicles through information interaction and mutual coupling. So it is a special multi-agent system. In [10], a multi-agent system is a dynamic system formed by multiple agents with independent capabilities through the interaction of a certain information topology. It was first used to study natural behavior. For example, Reynold et al. [11] established a distributed behavior Boid model of an animal group according to the characteristics of bird groups and gave three rules for nodes based on neighborhood information feedback:

1) Collision avoidance

2) Velocity matching

3) Flock centering

Using graph theory and stability theory, Jadbabaie et al. [12] gave the conditions for achieving consistent speed and direction in a multi-pointer system under undirected communication topology . Li et al. [13] pointed out that a unified framework can be used to analyze the consistency problems of multi-agent systems and complex network synchronization problems and proposed the concept of consensus region . Zheng Xiang et al. [14] put forward the concept of four-element modeling and summarized the previous work, and successfully used the four-element method to simulate under the linear controller . At present, the research on multi-agents has broadened to many other aspects, such as system heterogeneity [15], the influence of communication delay [16] and the requirement of communication data bit rate [17].

Compared with the traditional control of a single system, the coordinated control of multi-agents according to [18] has the following features:

- **Multiple control objects**. The system is formed by multiple relatively independent agents interacting and coupling through information flow.

- **Distributed control**. A single agent has certain communication and computing capacity limitations.
- **Consistency control objectives**. Consistency control objectives are embodied in this article as consistent speed, spacing, etc.

According to [10], multi-agent studies the interaction between information flow structure and dynamic control. Yang zheng et al. [19], the information flow topology of information interaction between individuals can be abstracted as a graph structure . It uses matrix analysis, linear control theory and other techniques to analyze and design it. This work studies the diversity of information flow in the platoon system from the perspective of multi-agent to design the controller and study the analysis of the control results of the controller by communication delay. This has theoretical value and engineering significance for improving the performance of vehicle platoon.

1.3 Modelling of the platoon system

The general view of platoon system is described as a series of autonomous vehicles that are directly grouped in the same lane. This thesis regards vehicle platoon control as a multi-agent coordinated control, and studies the influence of communication delay under different controllers. It can be proved that the coordinated driving can effectively reduce the probability of traffic accidents and make the driving of vehicles more stable.

In order to describe the intelligent coopera tive driving control strategy, researchers have established different concepts. The first is the concept of vehicle platoon control. Vehicle platoon refers to a series of closely spaced vehicles, in which the distance between the inter-vehicles is as short as 1-3m (the actual distance between the vehicles depends on the sensors and communication device used) according to the control requirements (Constant Distance (CD), Constant Time-headway (CTH) and the details will be introduced in the following chapters). Since each vehicle in the platoon knows the dynamic characteristics of the Lead Vehicle (LV), even such a short distance between the vehicles is sufficient for the vehicles. Generally, vehicles need to use radar and laser sensors to directly measure the speed and distance of the vehicle ahead [20]. In inter-vehicles communication, such as V2V and V2I, the position and distance of LV can be transmitted [4] [21]. Oncu et al. analyzed the influence of the effect of sampling,hold, and the network delays that occur due to wireless communication to the Cooperative Adaptive Cruise Control (CACC) system performance (string stability) [22]. Bernardo et al. proposed a method to analyze vehicle platoon from the perspective of dynamic network consistency. The conditions for system stability with time delay has been given [23]. Zheng et al. summarized these work a vehicle platoon can be intuitively divided into 4 basic modules, i.e. four-element vehicle platoon model based on algebraic graph theory, feedback linearization, and matrix analysis has been established [19][24]. which is:

- **Node dynamic** is to describe the dynamic behavior of a single vehicle.
- **Information flow topology** is used to describe the distance between two adjacent nodes.
- **Formation geometry** is used to describe the distance between two adjacent nodes.
- **Distributed control** is used to describe the design using information. The model can quantitatively study these four elements to characterize the state of the vehicle platoon, and it can also provide a framework for analyzing the performance of the vehicle platoon.

This thesis will rely on this model to design the corresponding controller and study the communication delay and other issues. For the convenience of introduction, below are some common concepts and definitions.

1) **Closed-loop Stability** The necessary and sufficient condition for closed-loop stability of a queue with linear time-invariant dynamics is that the characteristic roots of the closed-loop system are all negative real parts [14][25].

2) **String Stability** If a vehicle platoon is string stable, if and only if the disturbance in the platoon is not amplified towards the process of propagation along the vehicle platoon [26].

3) **Stability Margin** The stability margin of a vehicle platoon refers to the minimum distance between the stable closed-loop characteristic root and the imaginary axis, which is used to describe the decay speed of the initial disturbance [14].

1.4 Aims, Objectives and Contribution

1.4.1 Aims

The major aims of this thesis is to investigate the distribution controller's ability to lower the dynamic inter-vehicle distance in a vehicle platoon, consequently enhancing traffic efficiency. Then, to ensure traffic safety, investigate the impact of time delays in the platoon. Finally, it will develop real experiments to test the theoretical design's practicality.

1.4.2 Objectives

The main objectives of the project are:

- **Four-element model** This thesis will use the four-element model to divide the vehicle platoon into four basic modules to analyze, 1) Node dynamics; 2) Information flow topology; 3) Geometry configuration; 4) Distributed controller. It will use this basic vehicle platoon model to design the controller and study the influence of controller parameters and communication delay on vehicle platoon performance.

- **Research on the stability of vehicle platoon** This thesis will use the Routh-hurwitz stability criterion and Lyapunov theorem to study the controller stability area under different information topology structures and different control structures, and discuss the stability of linear homogeneous platoon with the changing of the error (spacing error and speed error) scale. It provides a way for the design of distributed controllers.

- **Robust performance analysis** The disturbance and noise will inevitably appear in the vehicle platoon system. To this end, this thesis will establish a simulation of vehicle platoon dynamics under general information flow topology, bi-direction topological structure and bi-direction with LV to analysis homogeneous platoon robust performance.

- **The design of the platoon distributed controller** This thesis will use the vehicle dynamics model to design vehicle controllers under different vehicle spacing requirements to meet different requirements. It use the above analysis methods to verify the performance and robustness of the designed controller in the vehicle platoon.

1.4.3 Contributions

The main contributions of the projects are shown in Chapter 4, 5 and 6 in detail. These are:

- A novel Fuzzy-PID controller was designed with V2V communication in the car-following system and vehicular platoon system in this thesis. The close-loop stability and string stability has been verified by using Routh-Hurwitz method and polynomial method. With the stability margin, it is easy for a designer to choose the value of the parameters in the controller. In addition, this work also tested the communication delay, controller parameters and the vehicle dynamic parameters with the platoon performance. Finally, the experimental results prove that this method is able to meet the modern control requirements of the vehicle platoon systems and the distance between the vehicles is gradually attenuated in the direction of the platooning, indicating that it can keep the string stability.

- This thesis designed a novel SMC with V2V and V2I communication to control the vehicular distance in a non-homogeneous platoon system. Secondly, in-depth investigation of vehicular communication structures in influencing system stability by employing Lyapunov Function (LF). Thirdly, the demonstration of the vehicle system lumped delay τ in a vehicle dynamic model utilizing system identification method.

Finally, it is exploring the features of SMC and its tolerance for communication delays in the simulation.

- In this work, the protocol and model for the V2V communication On-board Unit (OBU) with assisted CACC developed for platooning scenarios. In order to obtain precise positioning information, this work describes IMU/GNSS data fusion to achieve a highly precise positioning solution. Such high precision of positioning is required where vehicles in a platoon arrangement drive at very high speed. Thus, SMC has been implemented and the LF is established to analyze the stability of the string. The results prove that the following vehicles can reach the same velocity and acceleration as the leading vehicle in 5 seconds and the spacing error is less than 0.1m. In the field experiment, this work implemented cart test with a reference lead vehicle in the platooning system. The cart has IMU on board to collect the acceleration information. Then the control rule is applied for post-processing. The practical results are in line with those from the simulated experiment.

1.5 Layout of the thesis

This thesis is organized in seven chapters and one appendix. The rest of this thesis layouts as following.

The results of an extensive literature survey are presented in chapter 2. Firstly, the history and development of the vehicular platoon system are illustrated. The main techniques V2V and V2I communication methods for platoon system are summarised. The background of the platoon system is also introduced in this chapter. Secondly, vehicle platoon modeling is an important part of this thesis. Therefore, the reviews of the four-elements vehicle platooning model are introduced in this part. Finally, a comparison of the strengths and weaknesses of the common used controller for platoon is offered.

Chapter 3 introduces some mathematical tools and algorithms that will be used in this thesis. It includes building a four-element model, a communication network topology matrix, verifies the stability of platoon system and introduces the fusion algorithm of speed signals and position of vehicle in the platoon.

Chapter 4 develops an innovative approach using adaptive PID controller using fuzzy logic theory to keep variable time-gap between dynamic cars, particularly for platooning system. This study shows that robustness in maintaining gap between the dynamic cars, despite the specific vehicle model. In order to demonstrate robustness, it requires a set of information needed to be exchanged using V2V communication protocol. Time delay is a key effort for the quality of the platoon system based on the 4-elements model. The simulation results presented in this chapter show a significant improvement in keeping time-gap variable between the cars to have a safe and efficient flow of the platooning system. With CTH policy platoon system, the simulation presents the spacing error and speed with the interference of communication delay.

Chapter 5 proposes a SMC controller with a virtual lead vehicle information and V2V and V2I communication (global communication) to control EVs driving along a TEV lane. TEV is considered as a possible solution for Highway Transportation System (HTS). The main idea of TEV is that EVs drive within a dedicated lane at 200km/h with an inter-vehicle distance of 0.25 car lengths. The proposed controller is able to achieve these targets by introducing a new and simple method for determining the first order vehicle linear system identification and by guaranteeing that the designed controller shows non-homogeneous string stability in a platoon. The simulation presents the proposed controller achieved the goal of the TEV requirement with communication delay.

In order to obtain precise positioning information, chapter 6 describes IMU/GNSS data fusion to achieve a highly precise positioning solution. Such high precision of positioning is required where vehicles in a platoon arrangement drive at very high speed. If the control rule is based only on radar and internal sensors it cannot maintain a string stability compliant with CD policy. With the help of V2V communication, the dynamic information of the lead vehicle can be broadcast to any neighboring vehicle within the platoon system. Thus, SMC has been implemented and the Lyapunov function is established to analyze the stability of the string. In the simulation experiment, five vehicles are designed in the platoon system and these vehicles can obtain the information from both the leading vehicle and the preceding vehicle.

Chapter 7 details the the conclusion of this research results and findings. Furthermore, gives the details of the recommendation for future work.

In appendix A, based on Raspberry Pi and multi-sensors, this work designed a automated car with stop-and-go power systems, which is able to follow objects. This appendix presents the design of our RC car, as well as the longitude control architecture with PI control. The experiments carried out implement state-of-the-art electrical vehicle structure with autonomous control strategies. It also tests the dynamic performance of the car and that of tracking objects.

Chapter 2

Literature review

2.1 Vehicular platoon system

In the past two decades, the development of the automobile industry has brought great convenience to human transportation. But the rapid increase in vehicle ownership has also brought about traffic jams, road accidents and environmental pollution. Compared with widening or adding roads and other infrastructure, improving the technology of vehicles and improving the efficiency of transportation facilities can deal with the above-mentioned problems more economically and effectively. At present, many studies have proposed ideas based on individual vehicles. However, the control method for a single vehicle is limited in terms of improving safety, improving economy and reducing emissions. Research shows that the platooning of vehicles can significantly reduce traffic congestion, improve traffic efficiency and improve driving safety [27][28][29]. For example, Ali et al. [1] calculated that in TEV project, electric vehicles running in groups of 10 can reduce the drag of the following vehicles and increase fuel economy. In the introduction part of this thesis, the research on vehicle platooning control started from the PATH project in California in the 1980s [27][30]. Vehicle platoon is to form adjacent vehicles in a single lane and automatically adjust the longitudinal motion state of the vehicle according to the information of adjacent vehicles. Finally it achieves consistent driving speed in this desired configuration. In the various vehicle platoon projects introduced in the chapter 1, many basic issues have been studied, such as the main goals of the platoon, the distribution of control, the control architecture and sensing technology. In addition, more advanced and complex control strategies are also applied to the vehicle queue to achieve better queue performance. For example: Dunbar and Derek (2012) applied predictive control technology to vehicle platoon, by designing a distributed rolling time domain predictive controller and obtained a sufficient condition to ensure stability [31]. Ploeg et al. (2014) proposed a H_∞ controller design synthesis method, in which the platoon stability can be guaranteed explicitly. With the development of network communication technology, Li (2018) proposed an Adaptive Cruise Control (ACC) fuzzy control algorithm based on vehicle communication [32]. The information of the leading vehicle can be broadcast to the following vehicles. An SMC control algorithm based on this network structure can effectively reduce the following distance and improve road traffic efficiency, such as [33][34]. However, the control structure will be affected by network delay, packet loss, etc. Therefore, this thesis aims to study the influence of communication delay on advanced controllers to provide a reference for the design of vehicle platoon system.

2.2 Vehicle-to-Vehicle and Vehicle-to-Infrastructure communications in a platoon system

V2V and V2I communication technology plays an important role in cooperative driving, because all the necessary driving information of other vehicles needs to be transmitted to each other to assist driving decision-making. Researchers have designed, implemented and tested different V2V communication models in the past decade.Such as the Kaltwasser and Kassubek et al. proposed the Cooperative Optimized Channel Access for Inter-vehicle communication (COCAIN) model [35], Verdone et al. demonstrated the Telecommunication Network for Cooperative Driving (TELCO) model [36]. Tokuda et al. developed the Dedicated Omni-purpose inter-vehicle communication Linkage Protocol for Highway automation (DOLPHIN) model [37]. Based on the medium of V2V communication technology, different systems can be roughly divided into the following three categories: infrared, optical fiber and radio. Reference [38] indicates that the optical transmitter and receiver using LEDs and condenser lenses are within $\pm 20^{\circ}$ communication direction, the communication distance is 30m and the number of light-emitting diodes is 8. This equipment can guarantee the communication quality with the error rate to as low as 8-10 bit or even lower. However, the V2V communication system based on the optical transmitter can only be applied to vehicle formation control, which is a longitudinal vehicle platoon system. This is because the optical transmitter and receiver are installed at both ends of the car.

Most V2V communication systems are using VHF waves and microwaves in broadcasting. The most important issue that needs to be resolved is that the V2V broadcast link is affected by multipath fading and interference. To overcome these issues, they have proposed and tested different communication protocols in the fast and changeable traffic environment. However, there is still no standard that is accepted worldwide. The traditional realization method of V2V communication technology links the vehicles through additional remote service stations (i.e. the base station tower [39]). The driving information of the vehicle is first transmitted to the service station and then broadcast to other vehicles, or the vehicle needs to find other vehicles by querying the service base station. However, such a method requires considerable cost to establish and maintain a service station. Different from the above methods, many new designs use point-to-point self-organizing networks to realize vehicle information interaction. As mentioned in [40], the peer-to-peer self-organizing communication network integrates the following four valuable characteristics: self-organizing connectivity, location-to-point network, short-range and interpersonal communication. However, due to the characteristics of high-speed mobility and various curse behaviors, the performance of the V2V communication network still needs further discussion. Therefore, the communication delay problem in the operation of high-speed vehicles is a challenge that cannot be ignored. So this thesis will focus on the communication delay.

2.3 Tracked Electric Vehicle System

The TEV project is founded by Mr. Will Jones, CEO of Philadelphia Scientific [8]. TEV is a prefabricated track system and therefore costs less than rail or motorway. The size and the weight of the TEV unit is compact so that it can be placed on bridges and in tunnels. In safety consideration, the restricted-access tracks with side barriers can avoid the switch lane collision. In the requirement of the TEV project, fully autonomous vehicles in platoons will drive faster than urban trains at high speed 200km/h (125mph) with no overtaking. The TEV carrying capacity is equivalent up to 17 lanes of traditional highways. Ali et al [1] found that the designed TEV project is highly efficient due to 1) Steady speed, 2) Reduced air drag due to the convoy system, 3) Electrical power is directly delivered to the motor.

The Electricity Vehicle (EV) geometry effect is represented in Fig.2.1[1] using three different car brands, the Nissan Leaf, Tesla Model-3 and the TEV's streamlined EV, which have different aerodynamic parameters. The platooning effect is represented by comparing the driving of any EV in a platoon with an inter-vehicle distance of 0.25 car length with the same EV driving individually.

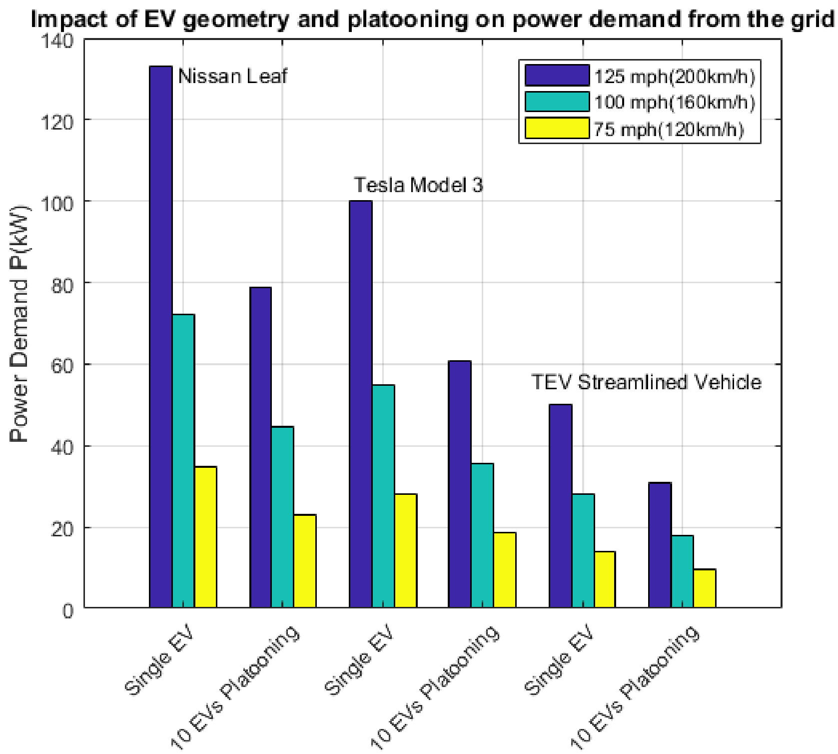


Fig. 2.1 Power demand from grid

The main advantage for using a car length of 0.25 to 0.35 is that the front car has the same drag coefficient than the followers. But the lead vehicle of a platoon has a greater air resistance as shown in Fig.2.2[1], which means it has higher energy consumption. C_d is the coefficient of air resistance, which is usually an experimental value. It is related to the windward area and the overall shape of the vehicle in this figure. C_d in isolation means the coefficient of the lead vehicle. C_d in platoon system means this parameter on the vehicles in the platooning. It shows that in dynamic road charging power consumption is mostly dominated by the speed of the EV. It can be clearly seen that the power demand of the TEV's streamlined EV is around a third of Nissan Leaf, which verifies the significant impact of EV geometry on the power demand from the grid. On the other hand, the platooning of any brand of EVs at an inter-vehicle spacing of 0.25 car length leads to about a 40% reduction in power demand.

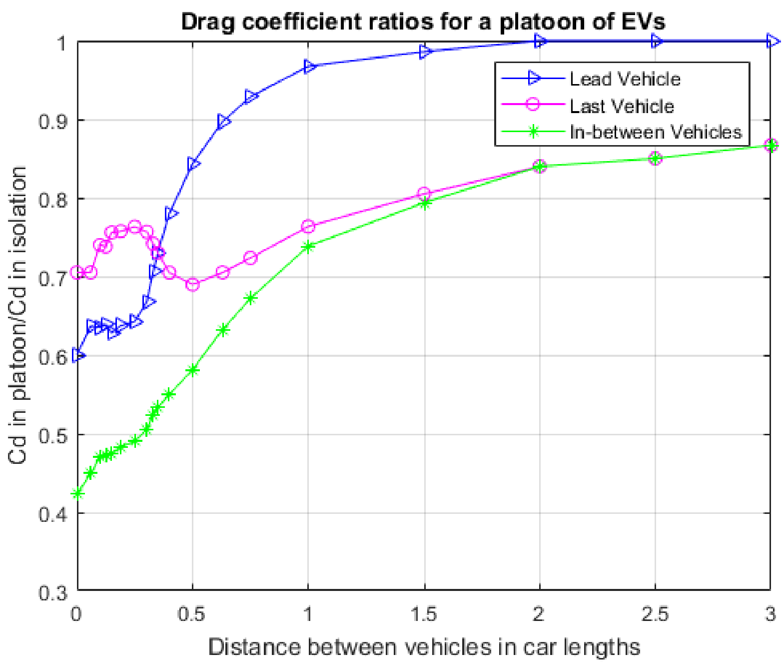


Fig. 2.2 Drag coefficient ratio as a function of distance

2.4 Four-Element model of the platoon system

For vehicle platoon system, most of the existing research studies are case by case, which is usually designing a type of analysis method for a specific configuration and lacks a general modeling and analysis framework. The application scenarios in the study of vehicle platoon are typically straight roadways, with no passing or turning. As a result, it can be reduced to a one-dimensional system. In this thesis, the platoon system is regarded as a one-dimensional multi-agent system and a four-element modeling framework of the vehicle platoon dynamics system is established to provide a feasible unified perspective for the analysis and control of the vehicle platoon system based on Zheng et al' s work [19][14][41]. This section introduces the four-element modeling framework of the vehicle platoon and summarized the related work.

From the perspective of one-dimensional multi-agents, vehicle platoons are actually a dynamic system composed of multiple single vehicle individuals controlling nodes through information interaction and then coupling each other. In the platoon system, a single vehicle only uses the information of the vehicles in the neighborhood to make control decisions and finally control the whole platoon system. Overall, A vehicle platoon can be directly decomposed into four basic modules as the following sections.

2.4.1 Node vehicle dynamic model

Most studies only focus on the vehicle's longitudinal dynamics and only a few scholars discuss the longitudinal and lateral integrated control of the vehicle simultaneously, such as in the appendix A of this thesis. This system is more accurately reflects the situation of a single vehicle. However, because the study of the vehicle platoon is only considering the vehicle's longitudinal movement, the researchers will not focus too much on this system. The research of lateral dynamics are usually described by bicycle models, for example [26]. So this work only reviews the longitudinal dynamics modeling methods.

The mainstream vehicle node dynamics model is approximated by Newton's second law. As in reference [30][42]. The vehicle node dynamic model is as follows:

$$\begin{cases} m_i \dot{v}_i = F_i - K_{di} v_i^2 - d_{mi} \\ \dot{F}_i = -\frac{F_i}{\tau(v_i)} + \frac{u_i}{\tau(v_i)} \end{cases} \tag{2.1}$$

which F_i stands for the engine force for the vehicle. $K_{di}v_i^2$ stands for the air drag force. d_{mi} is the mechanical resistance. $\tau(v_i)$ is the engine time coefficient when the vehicle velocity is v_i. m_i is the vehicle mass. u_i is the engine pedal input i.e. acceleration pedal. Then it brings the equation 2.1 to the size N vehicle platoon. This work used exact linearization methods and differentiating both side of equation 2.1, which brings[30]:

$$\dddot{x}_i = b_i(\ddot{x}_i, \ddot{x}_i) + a_i(\dot{x}_i)u_i \tag{2.2}$$

which:

$$a_i(\dot{x}_i) = \frac{1}{m_i \tau_i(\dot{x}_i)} \tag{2.3}$$

and

$$b_i(\dot{x}_i, \ddot{x}_i) = -\frac{1}{\tau_i(\dot{x}_i)}(\ddot{x}_i + \frac{K_{di}}{m_i}\dot{x}_i^2 + \frac{d_{mi}}{m_i}) - \frac{2K_{di}}{m_i}\dot{x}_i + \ddot{x}_i a_i(\dot{x}_i)u_i \tag{2.4}$$

In reference[30], it gave the control law which is:

$$u_i(\dot{x}_i, \ddot{x}_i) = \frac{1}{a_i(\dot{x}_i)}(-b_i(\dot{x}_i, \ddot{x}_i)) + c_i) \tag{2.5}$$

Thus, the close-loop dynamic of every vehicle in the platoon is [30]:

$$\dddot{x}_i = c_i \tag{2.6}$$

where c_i is an exogenous input to the ith vehicle dynamics, b_i and a_i are intermediate replacement functions and have no practical meaning. The node control diagram of this node dynamic is as the following figure 2.3[30]. Δ_i is the spacing error of the inter-vehicle space. The above vehicle dynamics modeling is a classic model. In the vehicle node dynamic, there are some strong nonlinear parts such as the engine, transmission, quadratic term of air resistance and braking. Therefore, the longitudinal dynamics of the vehicle is nonlinear. Yue et al. [43] decomposed the vehicle longitudinal dynamics model into a linear part and a non-linear part. It regarded the non-linear term as interference and used the neural network

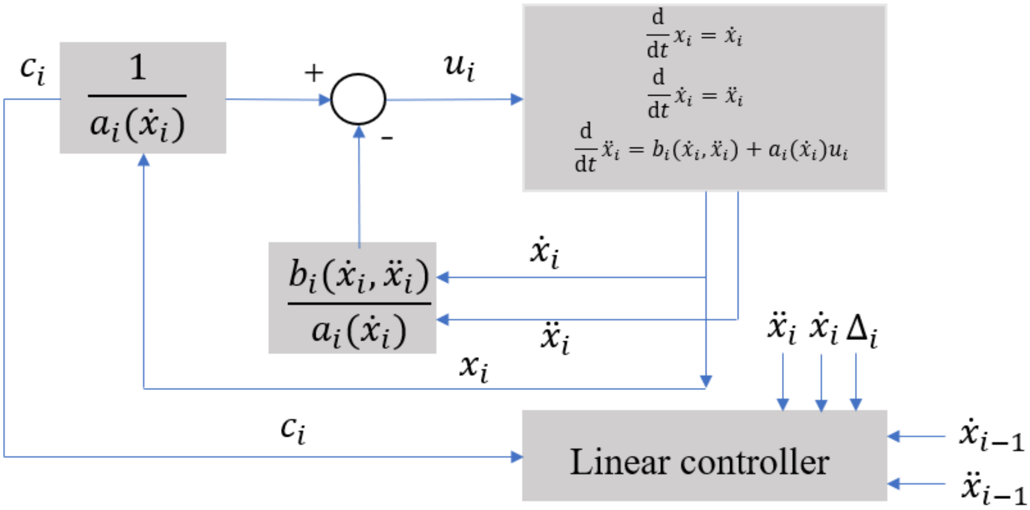


Fig. 2.3 The ith vehicle control input c_i linear model

method to estimate the non-linear term. However, with nonlinear models, it is difficult to analyze the performance and the limits of specific platoon systems. In fact, in order to facilitate theoretical analysis, many studies use linear models to describe the longitudinal dynamics of vehicle nodes, Including 1) Single integrator Model [44][45][46], 2) Double integrator model [47][48][23], 3) Third-order model [30][49][50][51][52], 4) Single input single output model [53][54].

In addition, Swaroop and Rajagopal et al. considered the Autonomous Intelligent Cruise Control (AICC) problem of traffic flow stability as the so-called spring effect or string stability problem. The inter-vehicle space oscillation through the platoon and causes its length to expand or contract. Their main research method is to use longitudinal control to reduce the spring effect [55][56][57].

2.4.2 Information topology structure

In the existing research, the information flow topology involved is relatively simple, focusing only on a few common structures. Due to the development of the ACC and CACC, the predecessor-following topology has been a trend in the last decade [58]. With the development of communication technology, V2V communication has rapidly become popular and a large number of different types of information flow topologies can be generated in the vehicle platoon. So in this field, based on the sensor and radar some researcher study the classical ACC and with the communication it changes to CACC, such as [59]. With the development and proposal of modern graph theory, a large number of different types of information flow topology structures can be generated in the vehicle platoon, such as the two-predecessor and multiple-predecessor following topology. There are also many scholars who have produced novel research on new topological structures, such as Yi et al. [60], which jth vehicle receives information via sensors from the $(j-1)$th vehicle and via V2V communication receive information from the $(j-2)$th vehicle. So It can be regard as a PF structure. In order to study the information topology structure, it is easier to establish a mathematical model to analyze the stability of the entire platooning. The numerous communication structures are organised in this thesis according to the four-element modelling for the benefit of future scholars as follows:

Table 2.1 The research on vehicle platoon topology structure in recent years

	Information topology structure	
Predecessor-following topology (PF)& ACC	Predecessor-leader following topology (PLF) & CACC	Bidirectional topology (BD)
[61][62][63][64][34] [65][32][50][51][66] [22][67] citelin2011optimal[77][78][54][79] [80]	[68][69][33][31][24] [26][70][71][72]	[48][73][74][75][76]
Bidirectional-lead following topology (BDL)	Two-Predecessor-following topology (TPF)	Two(or more)-Predecessor-leader-following topology (TPLF)
[53][81]	[66][82]	[83]
Undirectional topology (UD) [84] [29]		

2.4.3 Formation geometry of platoon system

The control target of the vehicle platoon system is to ensure that the speeds of the following vehicle and the leading vehicle are the same, while maintaining the desired geometric configuration between adjacent vehicles. For the convenience of future researchers' research, this work primarily collects three exemplary geometric configuration documents as follows:

- CD [50][53][47][31]
- CTH [66][54][23][22][51]
- Nonlinear distance (NLD) [49][85]

For the CD configuration, the expected distance between two adjacent vehicles has nothing to do with the speed of the vehicle and a higher traffic density can be achieved. For the CTH configuration, the expected distance between two adjacent vehicles and the speed of the self-vehicle are linear, which is like the behaviour of a vehicle controlled manually. But it limits the achievable traffic density. In the existing research of CACC and ACC, this geometric configuration is also used. However, because this type of research has formed its own system, there is no research on geometric configuration in the literature. For the NLD configuration, two adjacent vehicles expected distance between is a non-linear function of vehicle speed. Compared with the CD and CTH configurations, this method has the potential to improve the stability of traffic flow and increase the density of traffic flow at the same time. Since all the existing literature discusses the above configurations, this chapter will not count them one by one here and only selected the most representative articles.

2.4.4 Distributed controller used in vehicular platoon

For fuzzy control and sliding mode control, each has its own design logic flow to utilize its local information. The details shows in the following chapter. In this section, it only gives the design of the linear controller. As it is the most typical and classical controller, which is used by researchers to study the stability of platoon system [14][41]. Then, the following equation is the express of the linear controller:

$$
\begin{aligned}
u_i(t) = -\sum[k_{ij,p}(p_i(t-r_{ii}) - p_j(t-r_{ij}) - d_{i,j}) \\
+k_{ij,v}(v_i(t-r_{ii}) - v_j(t-r_{ij}) \\
+k_{ij,a}(a_i(t-r_{ij}) - a_j(t-r_{ij}))]
\end{aligned}
\tag{2.7}
$$

where the $k_{i,j,x}(x = p, v, a)$ is the control gain, r_{ii} is the time delay that vehicle i to obtain the data from itself. $p_{i,j}$, $v_{i,j}$ and $a_{i,j}$ donate the position, velocity and acceleration of vehicle i,j in this platooning. r_{ij} is the time delay from vehicle j to vehicle i. Since this equation has the time delay and the platoon node set, which is i, j. So it is used by researchers to study the communication delay and topology structure, such as [48][19][24][83][71].

2.5 Control methods in the platoon system

From the standpoint of control, the vehicle platoon can be thought of as a dynamic system made up of many single vehicle nodes that govern individual vehicles via information exchange and then are coupled together. Furthermore, it investigates how a single individual making decisions based on local information might lead to platoon behaviour synchronisation and consistency. Synchronisation and consistency are demonstrated by keeping the same speed, acceleration, and distance. While controlling these parameters, the stability of the control is reflected in the stable of the single vehicle and the entire platoon system. This thesis studies the control method based on the above analysis method. In recent years, the research related to this section is as the following table:

Table 2.2 Several control methods related to this thesis in recent years

Distribute controller		
Linear control	Fuzzy control	Slide mode control
[53][22][23][60][74] [86][70][44][71][77] [78] [67][87][81] [46] [45][44][79][80]	[88][69][65][89][90] [91][92] [93] [32]	[49][51][57][55][76][84] [34][94]

2.5.1 Linear control

Researchers consider the difficulty of theoretical analysis and the convenience of hardware implementation. Hence the common distributed controllers are the linear see the references in form as shown in Table 2.2. Under the linear controller, the closed-loop stability of the platoon system depends on the structure of the information flow topology. Therefore, the design of linear controller parameters usually studied case-by-case. For example, based on algebraic graph theory and matrix analysis, Zheng et al. analytically obtained the stable parameter region of a linear controller under different information flow topology [19]. For a vehicle platoon, the internal stability does not guarantee the Lyapunov stability of the platoon. The error may still be amplified during the transmission along the platoon. It may lead to the deterioration of vehicle economy and even rear-end collision. The advantage of the linear controller lies in its ability to analyze stability in combination with the topology. A large number of studies have shown that the platoon stability is closely related to the platoon configuration and information flow topology. Swaroop et al. (1999) showed that when a constant distance is used as the control target in vehicle platoon, it is difficult to ensure the string stability when the linear controller is used for the platoon under the PF topology [82]. The same result is also found in work [26], that is, under the radar control of ACC system, controlling the vehicle platoon with a constant distance cannot guarantee string stability. Barooah et al. (2009) pointed out that for the platoon under the BD topology with the control target of constant vehicle distance, the homogeneous linear controller is also difficult to ensure the stability of the vehicle platoon [48]. The research of Ghasemi et al. (2013) showed that the ability of following vehicles to obtain information about the leader is very important for ensuring the stability of the constant-vehicle platoon system [74]. At the same time, Zheng et al. (2014) pointed out that this ability is also very important for improving the performance of other aspects of the platoon, such as closed-loop stability and stability margin [24]. In recent years, there have been many types of controllers that can ensure the stability of the platoon. For example, a SMC can use lead vehicle information to ensure the stability of the platoon. It is of great significance in the study of distributed controllers for vehicle platoons.

2.5.2 Fuzzy control

Fuzzy logic control is a computer digital control technology based on fuzzy set theory, fuzzy language variables and fuzzy logic inference. In 1965, L.A. Zadeh founded the fuzzy set theory. In 1973, he gave the definition of fuzzy logic control and related theorems [95]. In 1974, British E.H.Mamdani first used fuzzy control statements to form a fuzzy controller and applied it to the control of boilers and steam engines and achieved success in the laboratory [96]. This pioneering work marked the birth of fuzzy cybernetics.

Fuzzy control is typically a nonlinear control, which belongs to the category of intelligent control. A major feature of fuzzy control is that it not only has a systematic theory, but also has a large amount of practical application. The development of fuzzy control initially encountered greater resistance in the west country. However, it has been rapidly and widely used in Japan. In the past 20 years, fuzzy control has made great progress both in theory and technology and has become a very novel and popular branch in automatic control field. Examples of its typical applications involve many aspects of production and life, such as fuzzy washing machines, air conditioners, microwave ovens, vacuum cleaners, cameras and camcorders in household appliances. In industrial control, there are water purification treatment, fermentation processes and chemistry control. In special systems and other aspects, there are fuzzy control of subway parking, car driving, elevators, escalators, steam engines and robots.

Fuzzy control also has a wide range of applications in the field of intelligent transportation. This thesis mainly studies the vehicle platoon branch in the field of intelligent transportation. In the past 5 years, Huang et al addressed the prioritized mission (dynamically balance the constraints of multiple missions) with the design of an adaptive fuzzy behavioural control from only kinematic level to the combination of both kinematic and dynamic levels [89]. These methods are successfully demonstrated in a platoon of mobile robots for avoiding obstacle. However, it does not consider the vehicles on the highway. Although the control method is very accurate, it is more suitable for laboratory use, without considering the actual traffic needs. This research is more suitable for group robot control. In the longitudinal control of vehicular platoon system, Dong et al proposed a fuzzy control method with estimating the uncertainty bound [65]. Under the premise of ensuring safety, it can obtain the performance of collision avoidance, uniform boundedness and uniform ultimate boundedness. The stability is proofed by the Lyapunov candidate function. However, its theoretical design is complicated and lengthy and only a three-car vehicle platoon is used in this simulation experiment. Under the condition of V2V, it is not conducive to analyze the information flow structure of the entire platoon. It is a sensor-dependent looking-ahead platoon structure. With the help of V2V communication, Lin et al designed an adaptive neuro-fuzzy predictor based control approach in CACC platoon system. In this fuzzy theory, a Takagi-Sugeno(T-S) fuzzy system has been used to approximate the unknown preceding vehicle model [69]. In addition, it also considered the fuel efficiency which is a new point in this field. The CarSim simulation in this work demonstrated the proposed control method from energy saving, safety and driving comfort. However, it lacks the mathematical proof of the string stability of the vehicle platoon and it only mentions that it satisfies the Lypunov condition. Ma et al proposed a two-layer (Hierarchical) fuzzy control combine with SMC approach to control the predecessor-successor platoon system [88]. The SMC part of this control is used for the string stability. This work include both the practical and simulation experimental with CD and CTH policy. In any case, this article did not consider the effect of the communication delay. In light of the fact the leader-follower was thought of so there was no information flow structure study. Based on the study of CACC and 4-elements model of vehicular platoon system, Li et al designed a Fuzzy-PID controller based on the V2V communication in vehicular platoon system [32]. In previous research, the CACC system is often studied separately and not included in the platoon system research. This work used the 4-elements method (node dynamic, formation geometry, information flow structure and distribute controller) to design a Fuzzy controller CACC platoon system. However, the communication delay and communication topology structures have not been discussed in this work. After studying the above papers, this work will focus on the relationship between the design of the vehicle platoon distribute controller and the communication delay. This work will explore the relationship between the quality of the vehicle platoon and various parameters. Make theoretical research and contributions in advance for the popularization of communication equipment in the intelligent transportation in the future.

2.5.3 Slide Mode Control

Sliding mode control (SMC), which is also be known as variable structure control. It's simply a type of nonlinear control in which the nonlinearity expresses itself as control discontinuity. The distinction between this control method and others is that the system's 'structure' is not fixed, but can vary on purpose depending on the present state of the system (such as deviation and its derivatives, etc.) in the dynamic process. The system is compelled to follow a predetermined state trajectory known as 'slide mode'.The SMC has the advantages of fast reaction, matching parameter changes and disturbances, no online identification of the system, and simple physical realisation because it may be created and has nothing to do with the object parameters and disturbances. Based on the slide mode control theory [97], the SMC method has two advantages:

- The sliding mode can be designed with few adjustment parameters and fast response speed.
- Not sensitive to disturbance (robust).

SMC is essentially a kind of non-linear control. Generally, its non-linearity is the discontinuity of control, that is, the structure of the system is not fixed and it can be purposefully based on the current state of the system during the dynamic process. Constant changes force the system to follow a predetermined sliding mode state trajectory. To explain a real system, now

Fig. 2.4 Vehicle model

suppose there is a small vehicle on the ground as Fig.2.4. It is at the coordinate axis point x_0 and it has a speed away from the coordinate axis. The question now is how to design a controller to make it move as needed (target velocity and position).

Now write the equation of state for this vehicle:

$$\begin{aligned} \dot{x} &= v \\ \dot{v} &= u \end{aligned} \tag{2.8}$$

where x is the position of vehicle, v is the velocity and u is the controller output. e_1 and e_2 are the error of the position and velocity. So the control target is e_1 and e_2 both equal to 0 as shows in Fig.2.5

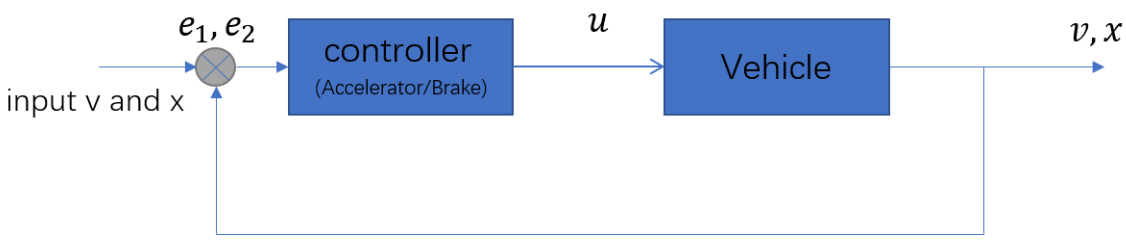


Fig. 2.5 System block diagram

Then it has to design the slide surface as:

$$s = ce_1 + e_2 \tag{2.9}$$

where c is a non-zero constant. It is also the turning parameter of the controller. Then it tried to set slide surface $s = 0$, thus: $\begin{cases} ce_1 + e_2 = 0 \\ \dot{e}_1 = e_2 \end{cases} \Rightarrow ce_1 + \dot{e}_1 = 0 \Rightarrow \begin{cases} e_1 = e_1(0)e^{-ct} \\ e_2 = -ce_1(0)e^{-ct} \end{cases}$
It can be seen that the state will eventually tend to 0 and it is approaching at an exponential speed. which means, when $t = \frac{1}{c}$, it has completed 63.2% of the process of approaching 0. At $t = \frac{3}{c}$, it has completed 95.021%. Adjusting the value of c can adjust the speed at which the state approaches 0. So if $s = 0$ is satisfied, the state of the system will tend to 0 along the sliding surface ($s = 0$ is the sliding surface).

Next step is to design the reaching law, which designs the relationship between s and u. u is the controller output, which means the value can give to the vehicle as the figure 2.5 shown.

If the target velocity v and position x is constant so:

$$\dot{s} = c\dot{e}_1 + \dot{e}_2 = c\dot{e}_2 + u \tag{2.10}$$

which $\dot{s}$ is the reaching law, the common used reaching law are:

$$\begin{cases} \dot{s} = -\varepsilon sgn(s), \varepsilon > 0 \\ \dot{s} = -\varepsilon sgn(s) - ks, \varepsilon > 0, k > 0 \\ \dot{s} = -k|s|^{\alpha}, 0 < \alpha < 1 \end{cases} \tag{2.11}$$

$$sgn(s) = \begin{cases} 1, s > 0 \\ -1, s < 0 \end{cases} \tag{2.12}$$

where ε,α and k are the parameters of the controller. These constants affect the convergence speed of the system. According to the above law of reaching, the expression of the controller u can be obtained. For $\dot{s} = -\varepsilon sgn(s), \varepsilon > 0$, it can obtain $u = -ce_2 - \varepsilon sgn(s)$.So apply the control of u to the vehicle, then the vehicle will finally stabilize at the target.

In summary, so the design step of SMC is to design the sliding mode surface first according to the state equation of the controlled object. Once the state reaches the sliding mode surface, it will reach a stable state in an exponential approach. Then the reaching law is designed to find the equation of the controller. The Lyapunov function is used as the guarantee of stability (details about lyapuniov theorem are given in Chapter 3) i.e. to ensure that $s = 0$ is reachable.

The above is the general SMC design method. In the vehicle platoon system, the SMC firstly designed by Swaroop and Hedrick [28], is based on a virtual leader and the real leader to broadcast information for the platoon, which is a Predecessor-following (PF) structure. With the development of v2v and V2I, Kwon and Chwa [76] improved his design into coupled SMC and used it for bidirectional topology. Wu et al. [98] designed Distributed sliding mode control (DSMC) for nonlinear heterogeneous platoon. This work is also based on the analysis of the four-element method. It handles the heterogeneous problem in the vehicle platoon. In the uncertain interaction topology structure, Gao et al. [84] designed a distributed smc, mainly from the perspective of communication protocol and practicability. Li et al. [34] introduced braking in vehicles and designed an integral-sliding mode control(ISMC) based on CTH. In terms of experimental design, Rupp et al. [99] studied a kind of smc control whose initial state is not zero. In the research of this article, based on the work of Zheng et al. [24] and Wu et al. [98], the four-element method is used to design the SMC and the research gap is filled in from the aspects of control design and stability verification. In the existing research, a single topology is designed. Combined with information graph theory, the SMC designed in this chapter can handle multiple information topology structures. It uses a matrix to analyze the string stability of a wide range of sorts of information topology structures.

2.6 Positioning system in vehicles – State of the Art

With the rapid development of the automatic EV industry and the communication technology, the V2V/V2I technology has been developing rapidly in recent years and is widely used in ITS. As one of the key technologies of the vehicle network, the vehicle navigation and positioning technology can not only provide location-based services, but also can be used for emergency rescue, vehicle scheduling and safety management of driving vehicles, etc., which has attracted widespread attention. GNSS can provide continuous real-time, high-precision three-dimensional position information for vehicles and is widely used. However, with the construction of modern cities, GNSS signals lose of lock (GNSS receiver no longer tracks the signal accurately) in blind areas such as dense urban high-rise areas, tunnels and underground garages, making it impossible to achieve reliable positioning alone. The combined navigation is usually composed of GNSS and wireless communications [100]. As an important technology in the V2V, the wireless communication system provides a full range of network connections for the V2V and can achieve positioning at the same time. It has developed rapidly in recent years. The existing positioning technology includes satellite navigation, inertial navigation and environmental feature matching. Yin et al. [101] combines 5G and GNSS signals for positioning. The simulation results show that the combined positioning accuracy can reach sub-meter level in environments with serious multipath interference such as indoors or indoor diplomatic circles. With the development of 5G technology, vehicle navigation systems can combine with 5G communications to achieve miniaturization and low-cost integrated navigation. Improving positioning accuracy without increasing costs has become a research trend. With the continuous improvement of satellite navigation systems, the accuracy of GNSS positioning will soon be improved to the decimeter level or even the centimeter level. However, the complexity of vehicle driving determines that high-precision positioning of autonomous driving requires deep fusion of GNSS and IMU signals, combined with environmental feature matching technology, to better cope with complex scenes such as high speeds, cities, loops, tunnels and extreme weather. Relying on any technology alone cannot meet the performance requirements of advanced autonomous driving. In this thesis, by studying the inertial device of the vehicle, collecting the speed and position information of the vehicle at every moment and combining this information with the GNSS position signal after returning this information to the user, a GNSS-based car integrated navigation system is proposed and a loose combination is established. The state equation and measurement equation of the GNSS/IMU integrated navigation system in the mode, the system provides real-time vehicle attitude information through the vehicle's own sensors (IMU sensor) and the position information provided by the GNSS system is used to achieve integrated navigation through Kalman filtering to meet the low-cost requirements of the vehicle platoon system.

2.7 Summary

This chapter undertook a literature review for this thesis. At first, it summarized the application of vehicular platoon system in modern transportation and the work summarized by other researchers. The advantages and disadvantages of several controllers in the vehicular platoon system are mentioned. Details of several projects mentioned in the chapter 1 has been also summarized in this chapter. Secondly, the related research of V2V communication is summarized. In the ongoing TEV project, it has proved the possibility of saving energy and improving efficiency. TEV tracks will have a significant construction cost, but it will be a drop in the bucket compared to the expense of highways and railways. Despite its massive passenger capacity, TEV will have a low build cost per mile. A two-lane TEV track, for example, will cost far less to construct than a four-lane Interstate Highway while providing many times more carrying capacity, a higher cruising speed, increased safety, and improved energy efficiency. It will also run on clean electricity rather than fossil fuels [9]. Thirdly, in the platoon system there are 4 terms which are node dynamic, information topology, formation geometry and distributed control. These four elements cover the entire platoon system research and this chapter also summarizes the existing literature on these four elements. Finally, three controllers related to this work have been summarized, which are linear controller, fuzzy control and slide mode control. Fuzzy controller will be used in chapter 4, chapter 5 described the slide mode control.In the appendix A it is shown that utilized basic linear controller knowledge to design a PI controller for car following system. In additional, it studied the newest hardware development status for the positioning of vehicle, which will contribute to chapter 6. In the next chapter, it will study the mathematical model for the vehicular platoon system and the hardware knowledge for the following chapters of the innovation work.

Chapter 3

Communication and Control methods in platoon system

3.1 Modelling of a typical platoon system

Figure 3.1, shows the concept of the 4 elements diagram which was first presented by Li and Zheng el. in [102]. By summarizing many researchers project, they separate the analysis process into 4 parts, Node dynamics, information flow, formation geometry and distributed controller. In my study it will use this method to establish the entire project.

1. Node dynamics (ND). Large part of studies on platoon system only on the longitudinal dynamical behaviors of ND. Study on [26], it has modeled the bicycle model which is usually used to describe the lateral dynamics. But for most research it only concern the longitudinal direction. The mainly vehicle longitudinal dynamics are nonlinear due to some nonlinearities phenomenon in the actual system. Such as engine, aerodynamics and braking system.

2. Information flow topology (IFT). This model concerns about the information obtains of its neighboring vehicles and how to influence the platoon system. Here it is mainly to study the string stability, stability margin and coherence behavior.

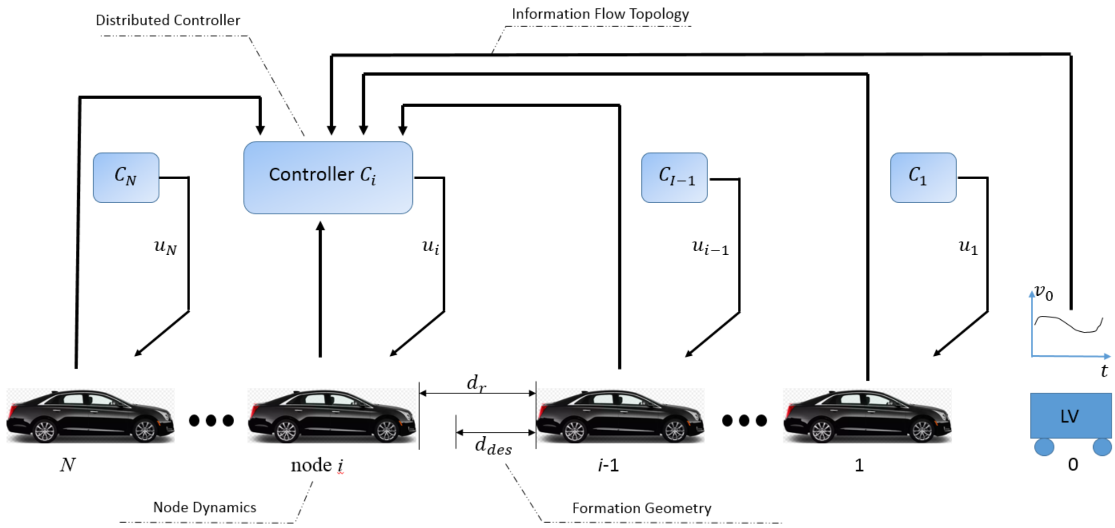


Fig. 3.1 Four elements analysis method

3. Formation geometry (FG). This objective is to track the movement of the vehicle in front. It is used for keeping the desired spacing, in other words, to control the speed of vehicle.

4. Distributed controller (DC), which is use the information of IFT and then implements the feedback control. Many researchers studied the different designed controller how to influence the performance of the platoon system.

3.1.1 Signal vehicle modelling in platoon system

Below are the assumptions made for the vehicle dynamic model:

1. Vehicles only experience rolling friction and aerodynamic force.
2. Vehicles used in this thesis do not use gear shift for torque conversion.
3. Only a 1-D longitudinal dynamics model is considered.
4. Vehicles are treated as ideal rigid thus ignoring the unbalanced left and right movement of cars.

Based on the above forces acting on a vehicle can be written as:

$$m\ddot{x} = F_x - F_r - F_{aero} \tag{3.1}$$

Where m is the mass of the car, $\ddot{x}$ is the acceleration, F_x is the traction force, F_r is the force of rolling friction and F_{aero} is the aerodynamic force. Thus, if the term $(F_r + F_{aero})$ is equal to F_x the car is driving at a constant speed. Equation (3.1) assumes that the wheel rolling resistance for each wheel is the same and that the car is driving on a straight lane without any elevation. If the term $(F_r + F_{aero})$ is less than F_x the vehicle accelerates and if it is greater than Fx the vehicle decelerates. In order to determine the velocity of the car it can use the following equation [26]:

$$v = \dot{x} = Rr_e\omega_e \tag{3.2}$$

where, ω_e is the motor speed, R is the gear ratio and r_e is the effective tire radius. With the details of the vehicle drive train technology the derivative of ω_e can be expressed as [26]:

$$\dot{\omega}_e = \frac{T_{net} - c_a R^3 r_e^3 \omega_e^2 - R(r_e F_r)}{J_e} \tag{3.3}$$

where, $\dot{\omega}_e$ represents the acceleration/deceleration of the motor-shaft speed. T_{net} is the net motor torque, c_a is the aerodynamic drag coefficient and J_e is the motor inertia respectively. From equation (3.2) and combining with equation (3.3), it has:

$$\ddot{x} = Rr_e\dot{\omega}_e = Rr_e\left(\frac{T_{net} - c_a R^3 r_e^3 \omega_e^2 - R(r_e F_r)}{J_e}\right) \tag{3.4}$$

In equation (3.4) none of the parameters can be influenced by the driver except the net motor torque T_{net} which is the required torque to produce F_x in (3.1). In EVs, electric drive trains are torque controlled and therefore T_{net} is a demand value. Consequently, as shown in (3.4) the demand of T_{net} results in an acceleration/deceleration represented by $\ddot{x}$.

Although equations above are ample to study the vehicle dynamics [103] vehicle platooning requires a different set of equations. The most common mathematical model for studying vehicle dynamics of a platoon is called double-integrator model [104] and its equation is:

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = u_i(t) \end{cases} \tag{3.5}$$

In this equation, $u_i\,(t)$ is the output acceleration in the platoon of each vehicle, where i ranges from 0 to N and, $N+1$ is the platoon size including the lead vehicle. Despite the fact, that this model considers the details of vehicle dynamics it is not suitable as a true representation of vehicles behaviors in a platoon as delays within the platoon system is not reflected. Therefore, many studies have used a 'lumped' delay τ_i to represent a delay in vehicle dynamics [105] [103] [106] and the fundamental equation used is:

$$\ddot{x}_i = \frac{1}{\tau_i s + 1} u_i \tag{3.6}$$

Adding τ_i changes (3.6) to:

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t), x_i(t) = \begin{bmatrix} p_i \\ v_i \\ a_i \end{bmatrix},$$

$$A_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_i} \end{bmatrix}, B_i = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau_i} \end{bmatrix} \tag{3.7}$$

Where p_i and a_i are the position and acceleration of vehicle i receptively.

3.1.2 Communication Topology Structure

In the classical vehicle platoon study, the information flow topology is relatively single and focusing only on a few structures, such as: predecessor-following topology [30][49][50], predecessor-leader following topology [47][31], bidirectional topology [48][75]. With the development of communication technology with the graph theory, V2V communication is popularizing rapidly. A large number of different types of information flow typologies can be generated in the vehicle platoon system, such as a two-front car following predecessor topology. The improvement of communication capabilities has resulted in diversified information flow topology. At this time, the string stability, controller design has been a problem in platoon study.

In a vehicular platoon system, the information flow topology has a close relationship with the way the vehicle obtains information from the neighbour vehicles. In early vehicle platoon study, it was mainly based on radar for information obtain, which meant that a single vehicle in the platoon can only get the dynamic information from the vehicle in front and the vehicle behind. With this limitation, the common information flow topology are PF(Predecessor Following) and BD,which show in Fig.3.2(1),(2). In fig.3.2, there are 6 types of communication topology structures. The arrow in the illustration represents the direction of information transfer, the recipient of the information at the front end of the arrow, and the transmitter of the information at the end of the arrow. The car is represented by the little circle in the platooning. At present, with the development of V2V communication technology rapidly, various information flow typologies have discovered in the platoon system. As the Fig 3.2 shows, Predecessor-leader Following (PLF) in Fig 3.2(3), Bidirectional Predecessor-leader Following (BPLF) [19] in Fig 3.2(4), Two-predecessor Following (TPF) [82] in Fig 3.2(5) and Two Predecessor-leader Following (TPLF) [24] in Fig 3.2(6).These are some common studied vehicular platoon structures.

3.1.3 Formation Geometry Modelling

The above-mentioned vehicle platoon must maintain synchronisation and consensus. So the target of vehicle platoon control is to require that the following vehicle and the lead vehicle maintain the same speed and the distance between adjacent vehicles is maintained at the desired distance. i.e. the difference of the velocity and acceleration of the vehicles are zero,

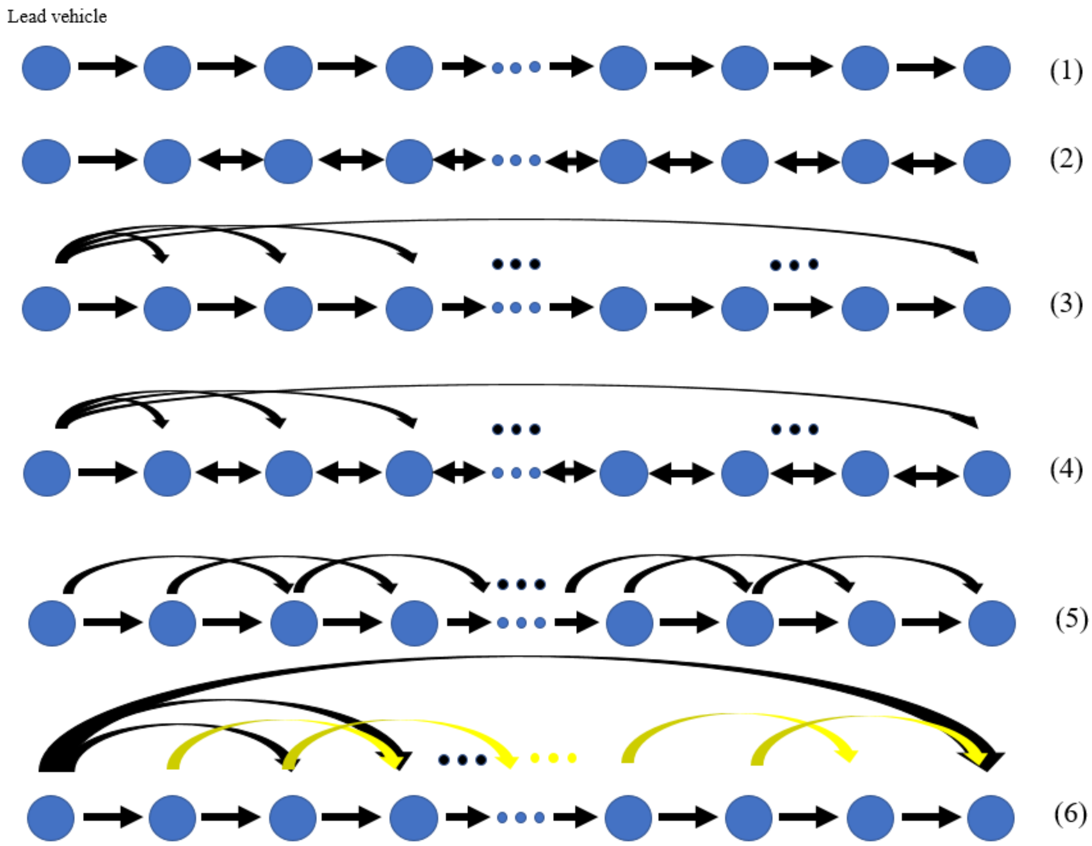


Fig. 3.2 Communication topology structures: (1) PF, (2) BD, (3) PLF,(4) BDL,(5) TPF,(6) TPLF

which is:

$$\begin{cases} \lim_{t\to\infty}(a_i(t) - a_0(t)) = 0 \\ \lim_{t\to\infty}(v_i(t) - v_0(t)) = 0, i \in N \\ \lim_{t\to\infty}(p_{i-1}(t) - p_i(t) - d_{i-1,i}) = 0 \end{cases} \tag{3.8}$$

where $a(t)$,$v(t)$ and $p(t)$ are the dynamic acceleration, velocity and position receptively of vehicle i. In this thesis, $d_{i-1,i}$ is the distance between two vehicles in one platoon system. In some research this distance not only stand for the distance between adjacent vehicles but also for any two vehicles as it summarized in [24]:

$$d_{i,i} = 0, d_{i,i-1} = -d_{i-1,i}, d_{i,j} = \sum_{k=i}^{j-1} d_{k,k+1} \tag{3.9}$$

So, the formation geometry model in one platoon system can designed by the desired distance d. In the CD policy, the distance is a constant value, so that:

$$d_{i,i-1} = d_0 \tag{3.10}$$

where d_0 is the constant distance value in this platoon system. In the CTH policy it changes to:

$$d_{i,i-1} = g(v_i) = t_h v_i + d_0 \tag{3.11}$$

For a CTH platoon, $g(v_i)$ is a linear function of the speed of the vehicle i. t_h is the constant time coefficient. A number of researchers optimize the function form from the perspective of ensuring platoon stability, traffic flow stability and improving traffic flow density. Basically as:

$$d_{i,i-1} = g(p, v, a) \tag{3.12}$$

For example, Zhou *et al* gave a function which is $g(v^2, a)$ [49].The parameters in this function can be determined by the real situation such as traffic flow, stability and platoon size. In my research, it discussed in details both CTH and CD policy in different scenarios in the following chapters.

3.1.4 Distributed Controller Design

The distributed controller uses the information of the neighboring vehicles to make feedback control to achieve the global coordination goal of the platoon. The unstructured controller requires that all vehicle nodes in the platoon have communication capabilities, that is, the information flow topology corresponds to a complete graph.

3.2 Communication algorithm in platoon system

3.2.1 Graph theory in communication topology

In order to characterize the information topology structure in the vehicle platoon system, Zheng *et al*. [14] [41] promote graph theory and matrix to capture this concept. This technology is widely used in communication flow structure. Assuming there is an N-size vehicle platoon system, it uses a directed graph $G_N = (v_N, w_N)$ to describe the information transmission. In this set, v_N denotes the vehicle set and $w_N = v_N \times v_N$ denotes the edge set. In a platoon system, there are two random vehicles i and j $(i, j \in N)$. Here, the edge set $w(i, j)$ represents vehicle j that can receive the vehicle's dynamic information from vehicle i. The definition of a directed path is a sequence of edge set $w(1,2)$,$w(2,3)$,$w(3,4)$,...,$w(k-1,k)$,$(k \leq N)$. This set is the directed path from node i to node k within the platoon system. Another definition is of the directed spanning tree, assuming that there is at least one vehicle that can acquire information from any other vehicle(s) directly or indirectly. In other words, this vehicle (node) has a directed path towards/for the others. This directed path can be called a directed spanning tree and this vehicle (node) can be called the root of this directed spanning tree. In [105], to control the platoon system, an assumption is made that G_{N+1} has a directed spanning tree with the lead vehicle ($N = 0$) as the root. Usually, the lead vehicle is globally reachable.

Before using a directed graph G_N, it provides a brief introduction related to matrix using the following steps:

1. Adjacency Matrix($A = [a_{ij}]$);

$$a_{ij} = \begin{cases} 1 & \text{if } (i,j) \in w_N \\ 0 & \text{if } (i,j) \notin w_N \end{cases} \tag{3.13}$$

   In this case, a_{ij} denotes vehicle i that can acquire the dynamic information from vehicle j. $a_{ii} = 0$ as there is no self-loop in this graph.

2. Laplacian Matrix($L = [l_{ij}]$);

$$L_{ij} = \begin{cases} l_{ii} = \sum_{j \neq i, j=1}^{N} a_{ij} \\ l_{ij} = -a_{ij} \end{cases} \tag{3.14}$$

3. Leader adjacency Matrix or Pining Matrix;

   The leader adjacency Matrix(LAM) represents the followers can obtain the information from the leader vehicle. so the LAM can be defined as;

$$P_N = \begin{bmatrix} p_1 & & \\ & \ddots & \\ & & p_N \end{bmatrix} \tag{3.15}$$

   Here, p_i can be 0 and 1, if $p_i = 1$ then vehicle i can receive the information from the lead vehicle, otherwise $p_i = 0$.

Fig.3.3 shows typical structures of vehicle communication: PF means the followers can only receive information from those in front. BD allows the vehicles to share their information with its neighbors. PFL permits the vehicles to receive dynamic information from the lead vehicle and its predecessor.Using Graph theory, it can write the LAMs and Laplacian Matrices for these structures as:

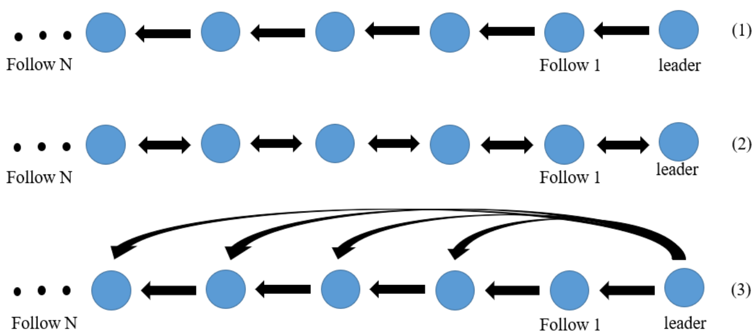


Fig. 3.3 Communication topology structures: (1) PF, (2) BD, (3) PLF

$$L_{PF} = \begin{bmatrix} 1 & & & \\ -1 & \ddots & & \\ & \ddots & 1 & \\ & & -1 & 1 \end{bmatrix}, P_{PF} = \begin{bmatrix} 1 & & & \\ & 0 & & \\ & & \ddots & \\ & & & 0 \end{bmatrix} \tag{3.16}$$

$$L_{BD} = \begin{bmatrix} 1 & -1 & & \\ -1 & 2 & \ddots & \\ & \ddots & \ddots & -1 \\ & & -1 & 1 \end{bmatrix}, P_{BD} = \begin{bmatrix} 1 & & & \\ & 0 & & \\ & & \ddots & \\ & & & 0 \end{bmatrix} \tag{3.17}$$

$$L_{PLF} = \begin{bmatrix} 1 & & & \\ -1 & \ddots & & \\ & \ddots & 1 & \\ & & -1 & 1 \end{bmatrix}, P_{PLF} = \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & \ddots & \\ & & & 1 \end{bmatrix} \tag{3.18}$$

It can be derived from formula 3.14 to obtain the above matrix that l_{ii} is a diagonal element that indicates the state of exchanging information by the node vehicle in the vehicle platoon. For instance, l_{22} equals the sum of vehicles in the platoon system that communicate with the second vehicle. The P matrix represents the information flow between the leader vehicle and all other vehicles. It shows the leader vehicle's uniqueness in the vehicle platoon. $L+P$ matrix is important in the platoon system closed-loop stability study. In [107], it has been proven that if the directed graph G_{N+1} has a directed spanning tree, then $L+P$ is defined as positive. This matrix is used to calculate the stability margin for linear node dynamic. In our new proposed SMC design in this chapter, it uses $L+P$ matrix methodology to prove the string stability of the platooning system.

3.2.2 Vehicular Communication protocol Study

The communication network in the ITS includes a wide area wired communication network, a wireless communication network, a short-range wireless communication network and a V2V/V2I communication network [108]. With the development of information, sensing, communication, network and other technologies, V2V communication technology has changed from independent driving in the past to one-way and two-way, symmetric and asymmetric information transmission and developed into self-assembly Network-oriented all-round communication network today. Although V2V communication technology has been successfully applied to advanced traffic management systems such as traffic guidance, non-stop toll collection and signal light control, V2V communication technology is still in the experimental stage. V2V communication generally adopts wireless access methods such as Dedicated Short Range Communication (DSRC) [109], WIFI(Wireless LAN) [110], Worldwide Interoperability for Microwave Access (WiMax) [111], Zigbee [112] and laser [113], infrared and ultrasonic transmission [114] methods.

For intelligent driving concern, self-driving car technology relies on communication, Artificial Intelligence (AI) [115], visual computing, radar, monitoring devices and Global Positioning Systems (GPS) to work together. It makes computers to operate vehicles safely and automatically without any human active operation. In the future, it requires massive and real-time data interaction in V2V and V2I communication. The realization of communication between self-driving cars also requires the network to transmit car navigation information, location information and vehicle dynamic data from various sensors of the car to the cloud which is the vehicle infrastructures or other vehicle terminals in real time. It also requires higher network bandwidth and lower network latency, which the technologies such DSRC cannot meet the requirement. Due to the development of the cellular network, it will be the trend to use 4G (The fourth generation of mobile phone mobile communication technology standards) and 5G in the V2V communication. The main idea of the cellular network solution is to use existing cellular network facilities to achieve workshop communication. Use 4G and 5G interfaces that are currently being researched to connect to the Internet. The advantages of cellular communication are obvious with low cost, basically only need to build an in-vehicle electronic platform, develop related software and network infrastructure, etc.

Consider the current V2V communication technology requirement, the key capability indicators of the 5G system have been greatly improved. 5G network transmission delay can reach milliseconds, ensuring the safety of vehicles at high speeds; 5G peak rate can reach

10−20 Gbit/s and the number of connections can reach 1 million / km^2 [116]. It can meet the communication needs of vehicles, people and transportation infrastructure in the future connected car environment. In this work, it will use 4G for the practical experimental as the communication method for V2V and V2I. Due to it can use the mobile phone to generate the 4G network and as the 5G is the trend in the future it also not be out of date in the next decade.

3.3 Stability for platoon system

This thesis focuses on the study of the stability area of the linear controller parameters of the platoon system under different information flow topologies. It provides methods for the selection of information flow topology and the parameter design of distributed controllers. Due to this, Routh-Hurwitz theorem, Lyapunov theorem and the concept of string stability in platoon system has been studied in this work.

3.3.1 Routh-Hurwitz theorem

Definition: If the coefficients in the first column of the Routh array table are all positive, the system is stable. which is to say all the roots of the characteristic equation are located on the left half of the root plane. If the coefficients in the first column have negative numbers, the number of changes in the signs of the coefficients in the first column is equal to the number of roots on the right half plane [117].

Assume it has a system characteristic equation as:

$$a_n s^n + a_{n-1} s^{n-1} + \cdots + a_1 s + a_0 = 0 \tag{3.19}$$

The coefficients in the equation are real number. $a_0 \neq 0$ and the system can not exist of zero roots.

Firstly, all coefficients in the characteristic equation are not equal to 0 and have the same sign, which is a necessary condition for system stability. Because any product of the first and quadratic factors containing only positive coefficients must also be a polynomial with positive coefficients. Therefore, the system is unstable if the characteristic equation lacks terms or has negative coefficient terms.

Secondly, if the coefficients are all positive numbers, it can make the Routh form as follows[117]:

$$\begin{array}{cccccc}
s^n & a_0 & a_2 & a_4 & a_6 & \cdots \\
s^{n-1} & a_1 & a_3 & a_5 & a_7 & \cdots \\
s^{n-2} & b_1 & b_2 & b_3 & b_4 & \cdots \\
s^{n-3} & c_1 & c_2 & c_3 & c_4 & \cdots \\
\vdots & \vdots & \vdots & & & \\
s^2 & e_1 & e_2 & & & \\
s^1 & f_1 & & & & \\
s^0 & g_1 & & & &
\end{array}$$

The first two rows of the Routh form are composed of the coefficients of the characteristic equation: The first row is composed of the 1, 3, 5, ... coefficients and the second row is composed of the 2, 4, 6, ... coefficients. The Routh form has $n+1$ rows, the bottom two rows each have 1 column, the upper two rows have 2 columns, respectively. The top row should have $\frac{1}{2}(n+1)$ columns or $\frac{1}{2}(n+2)$ columns. In the form, the third and forth row can calculate as [117]:

$$b_1 = -\frac{1}{a_1}\begin{bmatrix} a_0 & a_2 \\ a_1 & a_3 \end{bmatrix}, b_2 = -\frac{1}{a_2}\begin{bmatrix} a_0 & a_4 \\ a_1 & a_5 \end{bmatrix}, b_3 = -\frac{1}{a_1}\begin{bmatrix} a_0 & a_6 \\ a_1 & a_7 \end{bmatrix}, \cdots$$

$$c_1 = -\frac{1}{b_1}\begin{bmatrix} a_1 & a_3 \\ b_1 & b_2 \end{bmatrix}, c_2 = -\frac{1}{b_1}\begin{bmatrix} a_1 & a_5 \\ b_1 & b_3 \end{bmatrix}, c_3 = -\frac{1}{b_1}\begin{bmatrix} a_1 & a_7 \\ b_1 & b_4 \end{bmatrix}, \cdots$$

In the characteristic equation, the number of roots whose real part is a positive number is equal to the number of times the element signs in the first column of the Routh form are changed. Therefore, the necessary and sufficient condition for system stability is that all the coefficients of the characteristic equation are positive numbers and the elements in the first column of the Routh form are all positive numbers.

3.3.2 Lyapunov theorem for control system

From the Lyapunov theorem [118], given a nonlinear system as:

$$\dot{x} = f(x,t) \tag{3.20}$$

which,$x(t) \in \mathscr{D} \subseteq \mathbb{R}^n$ donates the state vector, $\mathscr{D}$ is the open set containing the origin, $t \in \mathbb{R}$ is the time parameter, function $f : \mathscr{D} \to \mathbb{R}$ is continuous in $\mathscr{D}$. Assume function f has a equilibrium x_e, i.e. $f(x_e,t) = 0$. The initial condition is $x_0 = x(t_0)$, the solution of system 3.19 is $x(t) = \phi(t;t_0,x_0)$. Thus,

(1) This equilibrium x_e is said to be **Lyapunov stable**: if $\forall \varepsilon > 0$, there exists a $\delta(\varepsilon,t_0) > 0$, when $||x_0 - x_e|| < \delta(\varepsilon,t_0)$, for every $t > t_0$ it has $||\phi(t;t_0,x_0) - x_e|| < \varepsilon$.

(2) The equilibrium x_e of the above system is said to be **asymptotically stable**: if x_e is Lyapunov stable there exists $\delta(\varepsilon,t_0) > 0$ such that if $||x_0 - x_e|| < \delta(\varepsilon,t_0)$, then

$$\lim_{t\to\infty} ||\phi(t;t_0,x_0) - x_e|| = 0 \tag{3.21}$$

(3) The equilibrium x_e is **exponential stability**: if x_e is said to be asymptotically stable and exists $\alpha, \beta > 0$, then

$$||\phi(t;t_0,x_0) - x_e|| \leq \alpha ||x_0 - x_e|| e^{-\beta t}, t \geq 0. \tag{3.22}$$

Lyapunov's second method for stability, which is now referred to as the Lyapunov stability criterion or the Direct Method. Now given a system $\dot{x} = f(x)$ and having a point of equilibrium at $x_e = 0$. Then, consider a function $V(x) : \mathbb{R}^n \to \mathbb{R}$, $V(x)$ has a first-order continuous partial derivative for each state. If

(1) $V(x)$ is positive define, i.e. $V(x) \geq 0$, if and only if $V(0) = 0$.

(2) $\dot{V}(x)$ is negative define, i,e, $\dot{V}(x) \leq 0$, if and only if $\dot{V}(0) = 0$. So $x_e = 0$ is local asymptotic stability and $V(x)$ is called Lyapunov function of this system.

(3) If $\lim_{||x||\to\infty} V(x) = \infty$, so $x_e = 0$ is the global asymptotic stability.

3.3.3 String stability

In [102], the definition of the string stability is that if a platoon system is string stable when and only when the disturbance in the platooning is not amplified during propagation towards to the end of the string.
Assume that δ_i and δ_{i-1} are the spacing errors of the i^{th} and $i-1^{th}$ vehicle in the platooning system. And $\widehat{H}(s)$ is the transfer function respect to the spacing error in the platooning. So

$$\widehat{H}(s) = \frac{\delta_i}{\delta_{i-1}} \tag{3.23}$$

Due to [26] and [55] the string stability has to consider two conditions as follows

1. The transfer function $\left\|\widehat{H}(s)\right\|_\infty \leq 1$
2. The impulse response function $h(t)$ which is the time-domain of the transfer function of $\widehat{H}(s)$ should not change sign.

3.4 Data fusion for vehicle positioning

3.4.1 Global Navigation Satellite System data

GNSS is a satellite based global navigation system which include GPS, Galileo, GLONASS and Beidou. Technically GNSS receivers(see Fig.3.4 and it also used in this work) can provide meter to submeter levels of accuracy [119]. On stationary GNSS receivers, the accuracy can reach to centimeter levels. However, the accuracy could be significantly diluted under suburban environments due to the high dynamic and multipath effects used in vehicle platoon. Thus, to obtain an optimal positioning solution, additional aiding sensors are required. IMU (Inertial Measurement Unit) or INS (Inertial Navigation Sensor) are commonly used for integrating navigation data [120]. Two types of GNSS/INS integration are widely used which are loosely and tightly coupled integration techniques. Loosely coupled integration refers to the direct integration of the position and velocity information from the GNSS receiver and the INS measurement. This is the most common integration method due to its easy implementation. On the other hand, integrating the pseudo range and pseudo range rate from the GNSS receiver and the INS measurement is called tightly coupled integration. This integration technique is more accurate and robust. However, it is more adopted for high grade INS, requiring highly accurate inertial measurement data.

Fig. 3.4 Leica Viva GNSS-GS10

3.4.2 Inertial Measurement Unit data

IMU (see Fig.3.5), usually composed of gyroscope, accelerometer and algorithm processing unit. Through the measurement of acceleration and rotation angle, it can obtain the motion trajectory of itself. It names the system which combines the IMU data, GPS and the information of the vehicle fusion algorithm that the autonomous driving IMU unit. This work mainly study this type of IMU. IMU only provides relative positioning information, which is the trajectory and posture of itself related to a certain starting position from a certain moment [121]. After fusing the relative positioning of IMU with the absolute positioning of Real-time Kinematic (RTK) GNSS, there are two irreplaceable advantages. Firstly, IMU can verify the self-consistency of RTK GPS results. If it can not be self-consistent, IMU can filter and correct the absolute positioning data. A simple example is if the absolute position of the RTK GPS output car changes greatly in a short period of time. It means the car has a great acceleration. However, the IMU finds that the car does not have such acceleration at this time, which indicates that there is a problem with the RTK GPS positioning. So

Fig. 3.5 Xsens IMU MTi-10

the IMU should take over the absolute positioning system. Secondly, the IMU can still provide sub-meter-level positioning accuracy for several seconds after the RTKGPS signal disappears. so it gives time for handling abnormalities for autonomous vehicles. In the same way, IMU can also perform track deduction on the relative positioning results when the relative positioning fails and maintain the relative positioning accuracy for a period of time. For example, when the lane line recognition module fails, based on the road sensed before the failure Information and IMU's deduction of the car's track can still allow the car to continue driving in the lane.

In summary, the positioning system relies primarily on high-precision maps, as well as inertial sensors from the IMU and GNSS, to precisely determine the vehicle's absolute position [122]. Among them, high-precision maps can provide assistance for vehicle environmental perception, provide information about road conditions beyond the visual range and help vehicles make planning decisions. The IMU is an autonomous navigation system that does not rely on external information. While the global positioning system uses satellite positioning to provide three-dimensional coordinates and speed at any location on the surface of the earth or near-Earth space GPS. The combination of the two can complement each other's strengths and jointly constitute an autonomous driving positioning and navigation system.

3.4.3 Kalman filter algorithm

Kalman filtering is an algorithm that uses linear system state equations to optimally estimate system state through system input and output observation data [123]. Since the observation data includes the influence of noise and interference in the system, the optimal estimation can also be regarded as a filtering process. Based on the MIT tutorial of the Kalman filter algorithm [124], this section briefly introduces the Kalman filter equation which it will be used in the following chapter.

Defining the system state as $X_k \in R^n$, the system control input as U_k and the system processing noise as W_k. k is the time index. Then it has the system state function as:

$$X_k = AX_{k-1} + BU_k + W_k \tag{3.24}$$

Define the observation $Z_k \in R^m$ and the observation noise as V_k and get the measurement function:

$$Z_k = HX_k + V_k \tag{3.25}$$

Assuming that W_k and V_k are independent and normal distributed white noise. The processing noise covariance matrix is Q and the observation noise covariance matrix is R, Thus:

$$W_k \sim N(0,Q)V_k \sim N(0,R) \tag{3.26}$$

A, B and H are the state transformation matrix. They are the adjustment coefficients in the state transformation, which are derived from the established mathematical model of the system. It can be a constant number.

Starting from the established mathematical model of the system, the Kalman filtering can be derived. which are predict equation and update equation. For explanation it defines that (1) $\widehat{X_k} \in R^n$, the state before the k-th step is known and then to predict the *priori* state estimation value of the k-th step(represents a priori, ȓepresents an estimate). (2) $\widehat{X_k} \in R^n$, when the measured variable Z_k is known and then to derive the estimated value of the *posterior* state of the k-th step. Then define the *priori* estimation error and the *posterior* estimation error which are:

$$\begin{aligned} e_k^- &= X_k - \widehat{X}_k^- \\ e_k &= X_k - \widehat{X}_k \end{aligned} \tag{3.27}$$

Covariance matrix of the *prior* estimation error is:

$$p_k^- = E[e_k^- e_k^{-T}] \tag{3.28}$$

and the covariance matrix of the *posterior* estimation error is:

$$p_k = E[e_k e_k^T] \tag{3.29}$$

where $E[\cdot]$ is the expected operation. Thus the following equation is the Kalman filter function. The linear combination of the priori estimate $\widehat{X}_k^-$ and the weighted measurement matrix Z_k and the difference between its prediction $H\widehat{X}_k^-$ constitutes the posterior state estimate $\widehat{X}_k$, which is:

$$\widehat{X}_k = \widehat{X}_k^- + K(Z_k - H\widehat{X}_k^-) \tag{3.30}$$

where the $Z_k - H\widehat{X}_k^-$ is measurement pre-fit residual. It shows the difference between the predicted value and the actual value. K is the Kalman gain. From above it can derive the Kalman gain $n \times m$matrix K_k which is:

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \tag{3.31}$$

Determining the Kalman gain is the key step of the Kalman filter, which can significantly affect the efficiency of the model.

The Kalman filter includes two main processes: estimation and correction. The estimation process is mainly to use the time update equation to establish a priori estimation of the current state and to calculate the current state value and error covariance estimation value in time to construct a priori estimation value for the next time state. The correction process is responsible for feedback and the measurement update equation is used to establish an improved posterior estimate of the current state on the basis of the prior estimation value of the estimation process and the current measurement variables. Such a process is called the estimation-correction process and the corresponding estimation algorithm is called the estimation-correction algorithm. The time update equation and state update equation of the discrete Kalman filter are given as follows:

Time update equation:

$$\begin{aligned} \widehat{X}_k^- &= A\widehat{X}_{k-1} + B\widehat{U}_{k-1} \\ P_k^- &= AP_{k-1}A^T + Q \end{aligned} \tag{3.32}$$

State update equation:

$$\begin{aligned} K_k &= P_k^- H^T (HP_k^- H^T + R)^{-2} \\ \widehat{X}_k &= \widehat{X}_k^- + K_k(Z_k - H\widehat{X}_k^-) \\ P_k &= (I - K_k H)P_k^- \end{aligned} \tag{3.33}$$

where A is the $n \times n$ state transformation matrix for X_{k-1}, B is the $n \times 1$ control input matrix for the control vector U_{k-1}. H is the $m \times n$ observation matrix and maps the real state space into observation space. P_k^- is the $n \times n$ priori estimation error covariance matrix. P_k is the $n \times n$ posterior estimation error covariance matrix. Q is the processing noise covariance matrix. R is $m \times m$ observation noise covariance matrix. I is the $n \times n$ identity matrix. K_k is a $n \times m$ Kalman gain matrix, which represents the proportion of predicted error and measurement error in the optimal state estimation process.

3.5 Summary

This chapter summarizes the mathematical tools and background knowledge used in the thesis. Firstly, it summarized the 4 elements method for the platoon system. It includes the signal vehicle modelling, communication topology design, the policy of the inter-vehicle space and the control method. Secondly, due to the develop of the communication technology, it studied the graph theory to build the corresponding matrix for different communication structure and the protocol has been also involved. Thirdly, the most important part is the stability of the system. In the subsection, it studied three main method to variety the vehicular platoon system stability which are Routh-hurwitz theorem, Lyapunov theorem and string stability. The above knowledge lays the foundations for this entire thesis. Never the less, this thesis also studied the sensors for the vehicles. In positioning of a vehicle, the GNSS and IMU data fusion is a significant part. Therefore, the background knowledge of GNSS, IMU and Kalman filter algorithm has been mentioned in this chapter. The next chapter's focus will be the fuzzy logic utilized in the vehicle platoon system. It will show how this is then used in the design of controller.

Chapter 4

Fuzzy logic theory to control the constant time-headway

This chapter develops an innovative approach using an adaptive PID controller using fuzzy logic theory to maintain a time gap between moving cars, particularly for a platooning system. Our study shows that robustness can be achieved in the control of the gap between the cars, despite the specific vehicle model. To demonstrate robustness, the platooning system study required data to be exchanged using a V2V communication protocol. This data-set of vehicle state dynamic information would come from in front of the vehicle. In addition, the communication delay was investigated in this chapter using different controllers. It also studies the performance of the unstable communication delay in the designed controller in the simulation. It concludes that, in CTH, this proposed controller is effective and more suitable for current road traffic than the original PID controller. Finally, it studies heterogeneous platooning with different communication delays, indicating this new controller can also meet future traffic needs. The simulation results presented in this chapter reveal a significant improvement in maintaining the time gap between the cars for a safe and efficient flow of the platooning system in different situations and with various vehicle parameters.

In the design of the novel controller, this work proposes to combine fuzzy logic theory with the conventional PID-control technology. The traditional method to design a PID controller begins by determining the parameters k_p, k_i and k_d (the gains of the proportion, integral and derivation of the errors, respectively). The concept of the designed adaptive fuzzy controller is based on the system error e and deviation rate of the system error ec through the continuous detection of e and ec during system operation. For the fuzzy controller, the parameters (k_p, k_i and k_d) are adjusted as the values of e and ec changed to satisfy the different requirements for control parameters. Therefore, the control system with the control target had better dynamic performance than only using PID control method. In other words, this fuzzy PID control is a self-adaptive controller. The block diagram is illustrated in Fig. 4.1.

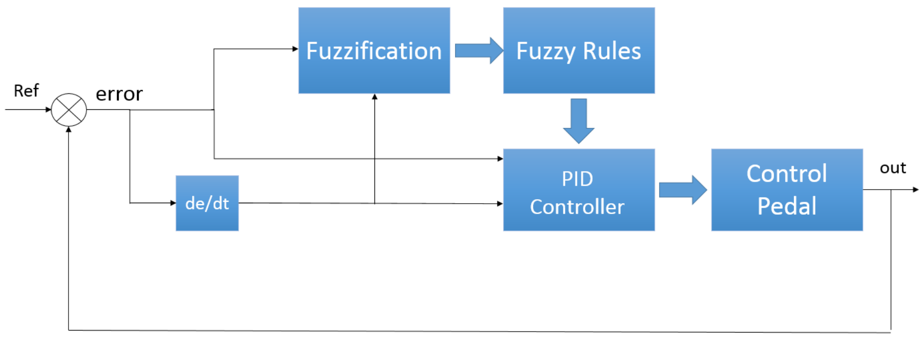


Fig. 4.1 Fuzzy control structure

4.1 Constant time-headway modelling with Fuzzy control

There are two ways to study the spacing between vehicles. In [26], the conventional CD approach is not suitable for autonomous control. Therefore, in this chapter, the CTH spacing policy, as Fig 4.2 illustrates, it will be used to study the platooning system. Compared with CD, CTH does allows the spacing to depend on the velocity as follows:

$$d_{des} = D_{min} + t_h \dot{x}_i \tag{4.1}$$

where d_{des} is the desired spacing, D_{min} is the safe distance between the leading and following vehicles after they stop and t_h is the constant time gap coefficient. The measured distance

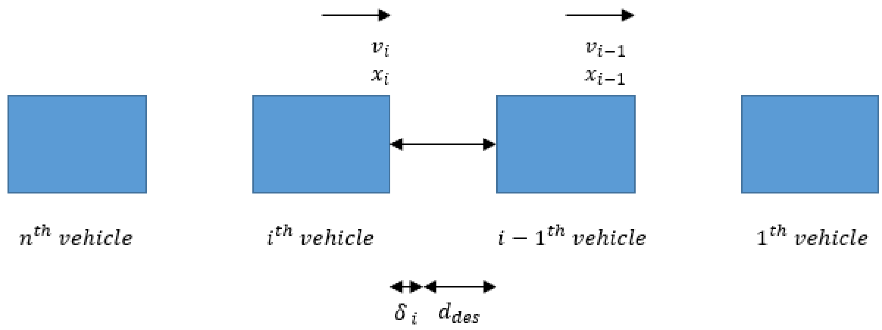


Fig. 4.2 Structure of the longitudinal control system

between neighbouring vehicles is as follows:

$$\varepsilon_i = x_{i-1} - x_i - l_{i-1} \tag{4.2}$$

and the spacing error is defined as

$$\delta_i = \varepsilon_i - d_{des} \tag{4.3}$$

Ioannou and Chien [125] developed the safety distance model with autonomous control law to be represented as

$$u_i(t) = \frac{1}{t_h}(\dot{\varepsilon}_i + \lambda_i \delta_i) \tag{4.4}$$

The value $\dot{\delta}_i = v_{i-1} - v_i$ can be determined. λ_i is the control gain, where $\lambda_i > 0$. In this study, the platoon system is assumed homogeneous, such that $\lambda_i = \lambda_{i-1}$. Differentiating both sides of the equation 4.3 yields

$$\dot{\delta}_i = \dot{\varepsilon}_i - t_h \ddot{x}_i \tag{4.5}$$

Substituting $\ddot{x}_i$ in equation 4.4, thus error dynamics can be obtained:

$$\dot{\delta}_i = -\lambda_i + \delta_i \tag{4.6}$$

4.2 General proportional–integral–derivative controller design

This section studies the original PID control for the upper control of the vehicle and then inputs the dynamic signal to the mechanical transmission part such as the motor. The overall system block diagram is shown in Fig 4.3 and the system can establish the transfer function such that

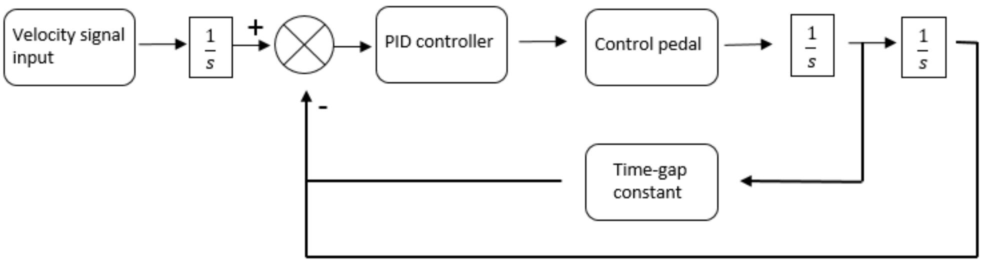


Fig. 4.3 PID control for CTH system

$$sY_{(s)} = (U_{(s)}\frac{1}{s} - Y_{(s)}\frac{1}{s} - Y_{(s)}h)(k_i\frac{1}{s} + k_p + k_d s)(\frac{1}{\tau s+1}) \tag{4.7}$$

and the transfer function $G_{(s)}$is

$$G_{(s)} = \frac{k_d s^2 + k_p s + k_i}{\tau s^4 + s^3 + k_d(1+h)s^2 + k_i(1+h)} \tag{4.8}$$

4.3 Routh-Hurwitz theorem for system stability

To determine the stability of this system, the Routh-Hurwitz [14] theorem was applied with the characteristic polynomial $D_{(s)}$ as follows:

$$D_{(s)} = s^4 + \frac{1}{\tau}s^3 + \frac{1}{\tau}k_d(1+h)s^2 + \frac{1}{\tau}k_p(1+h)s + \frac{1}{\tau}k_i(1+h) \tag{4.9}$$

Table 4.1 shows the Routh form.

Table 4.1 Routh Form

s^4	1	$\frac{1}{\tau}k_d(1+h)$	$\frac{1}{\tau}k_i(1+h)$
s^3	$\frac{1}{\tau}$	$\frac{1}{\tau}k_p(1+h)$	0
s^2	$\frac{k_d(1+h)-k_p(1+h)}{\tau}$	$\frac{1}{\tau}k_i(1+h)$	
s^1	$\frac{k_p(k_d-k_p)(1+h)-k_i}{\tau(k_d-k_p)}$	0	
s^0	$\frac{1}{\tau}k_i(1+h)$		

With the Routh-Hurwitz rule, the result is obtained with $\tau > 0$ and $h > 0$. The system is critically stable if and only if

$$\begin{cases} k_p > 0 \\ 0 < k_i < k_p(k_d - k_p)(1+h) \\ k_d > k_p \end{cases} \tag{4.10}$$

So, equation 4.10 is the stability margin for all the parameters of this close-loop controller.

4.4 String stability in designing constant time headway platoon system

In [102], string stability occursin a platoon system when the disturbance in the platooning is not amplified. In this case, δ_i and δ_{i-1} are assumed to be the spacing errors of the i^{th} and $(i-1^{th})$ vehicle in the platooning system. $\widehat{H}(s)$ is the transfer function with respect to the spacing error in the platooning. Thus,

$$\widehat{H}(s) = \frac{\delta_i}{\delta_{i-1}} \tag{4.11}$$

As in [26] and [55], the string stability has to consider two conditions:

1. transfer function $\left\| \widehat{H}(s) \right\|_\infty \leq 1$
2. impulse response function $h(t)$, which is the time domain of the transfer function of $\widehat{H}(s)$ and should not change the sign.

To design CTH controller, the parameters are calculated as follows with the two conditions:

$$\tau \dddot{x}_i(t) + \ddot{x}_i(t) = u_i \tag{4.12}$$

Substituting u_i from the equation 4.4, it has

$$\tau \dddot{x}_i(t) + \ddot{x}_i(t) = \frac{1}{t_h}(\dot{\varepsilon}_i + \lambda_i \delta_i) \tag{4.13}$$

Differentiating equation 4.5, it obtains

$$\ddot{\delta}_i = \ddot{\varepsilon}_i - t_h \dddot{x}_i \tag{4.14}$$

With the vehicle model in equation 4.12 and substituting $\dddot{x}_i$ it can get

$$\ddot{\varepsilon}_i = \ddot{\delta}_i + \frac{1}{\tau}(\dot{\varepsilon}_i - t_h \ddot{x}_i + \lambda_i \delta_i) \tag{4.15}$$

Substituting $\ddot{x}_i$, it has

$$\ddot{\varepsilon}_i = \ddot{\delta}_i + \frac{1}{\tau}(\dot{\delta} + \lambda_i \delta_i) \tag{4.16}$$

$$\delta_i = \varepsilon_i - t_h \dot{x}_i \tag{4.17}$$

$$\delta_{i-1} = \varepsilon_{i-1} - t_h \dot{x}_{i-1} \tag{4.18}$$

Subtracting and substituting yields

$$\delta_i - \delta_{i-1} = \varepsilon_i - \varepsilon_{i-1} - (t_h \dot{x}_i - t_h \dot{x}_{i-1}) \tag{4.19}$$

In Fig 4.3, $\dot{x}_{i-1} - \dot{x}_i = \dot{\varepsilon}_i$, which is the velocity error, so that

$$\delta_i - \delta_{i-1} = \varepsilon_i - \varepsilon_{i-1} + t_h \dot{\varepsilon}_i \tag{4.20}$$

Using the Laplace transfer function of equation 4.12 and substituting in equation 4.13, it can get

$$\frac{\delta_i}{\delta_{i-1}} = \frac{s+\lambda}{h\tau s^3 + hs^2 + (1+\lambda h)s + \lambda} \tag{4.21}$$

Swaroop's proof [55] for the string stability requires $h \geq 2\tau$ and the string stability can be achieved for only a time-gap that two times larger than the system lag. The proof is as follows:

1. Lemma 1 requires the following quadratic inequality:

$$a\omega^4 + b\omega^2 + c > 0 \tag{4.22}$$

$$a\omega^4 + b\omega^2 + c = a(\omega^4 + 2\frac{b}{2a}\omega^2 + \frac{c}{a}) \tag{4.23}$$

$$= a\left[(\omega^2 + \frac{b}{2a})^2 + \frac{4ac - b^2}{4a^2}\right] \tag{4.24}$$

With the given quadratic inequality, the following conditions should be satisfied:

1) $a, b, c > 0$

Or

2) $b < 0, a > 0, c < 0$ and $4ac - b^2 < 0$

Then, consider the following transfer function:

$$H(s) = \frac{\delta_i}{\delta_{i-1}} = \frac{s+\lambda}{h\tau s^3 + hs^2 + (1+\lambda h)s + \lambda} \tag{4.25}$$

Here, s is equal to $j\omega$. Then

$$H(j\omega) = \frac{j\omega + \lambda}{h\tau(j\omega)^3 + h(j\omega)^2 + (1+\lambda h)(j\omega) + \lambda} \tag{4.26}$$

Simplifying this equation yields

$$H(j\omega) = \frac{j\omega + \lambda}{(\lambda - h\omega^2) + j\omega(1 + \lambda h - \tau h\omega^2)} \tag{4.27}$$

Consider the conjugate complex number that $|x + jy| = \sqrt{x^2 + y^2}$; thus, $|H(j\omega)|$ is

$$\frac{|j\omega + \lambda|}{|(\lambda - h\omega^2) + j\omega(1 + \lambda h - \tau h\omega^2)|} = \frac{\sqrt{\omega^2 + \lambda^2}}{\sqrt{(\lambda - h\omega^2)^2 + \omega^2(1 + \lambda h - \tau h\omega^2)^2}} \tag{4.28}$$

For maintaining string stability, $|H(j\omega)| \leq 1$; hence,

$$\omega^2 + \lambda^2 \leq (\lambda - h\omega^2)^2 + \omega^2(1 + \lambda h - \tau h\omega^2)^2 \tag{4.29}$$

which is simplified to

$$\tau^2 h^2 \omega^4 + (h^2 - 2\tau h - 2\tau\lambda h^2)\omega^2 + \lambda^2 h^2 \geq 0 \tag{4.30}$$

Comparing with Lemma 1 results

$$\begin{cases} a = \tau^2 h^2 \\ b = h^2 - 2\tau h - 2\tau\lambda h^2 \\ c = \lambda^2 h^2 \end{cases} \tag{4.31}$$

1) If $a, b, c > 0$ – In these equations, since a and c both greater than 0, $b > 0$ is the only concern.

$$h^2 - 2\tau h - 2\tau\lambda h^2 > 0 \tag{4.32}$$

So, $h > \frac{2\tau}{1-2\tau\lambda}$. The upper limit of $\frac{2\tau}{1-2\tau\lambda}$ is when λ is infinitely small, i.e.

$$h > 2\tau \tag{4.33}$$

2) If $b < 0, a > 0, c > 0$ and $4ac - b^2 < 0$,

$$(h^2 - 2\tau h - 2\tau\lambda h^2)^2 - 4\tau^2 h^4 \lambda^2 < 0 \tag{4.34}$$

$$\sqrt{(h^2 - 2\tau h - 2\tau\lambda h^2)^2} < 4\tau^2 h^4 \lambda^2 \tag{4.35}$$

$$\left|h^2 - 2\tau h - 2\tau\lambda h^2\right| < \left|2\tau h^2 \lambda\right| \tag{4.36}$$

Since $b < 0$, the inequality changes to $-(h^2 - 2\tau h - 2\tau\lambda h^2) < 2\tau h^2 \lambda$ After simplifying it can obtain

$$h > 2\tau \tag{4.37}$$

In summary, these two conditions are true if and only if $h > 2\tau$. Thus, critical string stability is present when $h \geq 2\tau$. $H(s) = \frac{\delta_i}{\delta_{i-1}}$ is valid for [0, 1].

4.5 Fuzzy controller design in the platoon system

The traditional PID linear controller adjusts the PID parameters appropriately for different objects for effective control. However, the linear characteristics of the traditional PID controller can only obtain the desired result when near the working point. When far from the working point, the system performance will be worse or even unstable, owing to the non-linearity of the control system. The fuzzy logic method does not aim to establish the mathematical model of the whole system. The advantage is that the dynamic performance of the control can be significantly improved for operation from the working point. At the same time, the noise is also strongly suppressed and the system is robust. However, the fuzzy controller is essentially a non-linear control method. The performance of eliminating system errors is weak and high control accuracy is difficult to achieve. The use of only PID control or fuzzy control will not achieve adequate control results, while Fuzzy-PID controller is more effective. This combined approach has strong fuzzy control, better dynamic response, fast rise time, small overshoot and steady-state accuracy of the PID controller.

There is a proportional coefficient between the input and output of the fuzzy controller, specifically the scaling factor used in [126]. This coefficient reflects the proportional relationship between the fuzzy range and the actual range. For instance, the scope of the input and output of the fuzzy controller are both [-3, 3], while the actual error range is [-10, 10]; the error rate range is [-100, 100], the control range is [-24, 24]. Then it can calculate the quantisation. The factors are 0.3, 0.03 and 8 for the input/output, error rate and control, respectively. The selection of the scaling factor has a great influence on the control effect of the fuzzy controller and should be carefully selected according to the actual situation [126].

The membership functions of the fuzzy sets for the inputs and outputs are defined in the range of [-1,1]. The function uses a symmetric triangle with a 50% overlap of the neighbouring membership functions as in Fig 4.4, where *N* stands for *negative*, *Z* stands for *zero*, *P* is *positive*, *B* is *big*, *M* is *medium* and *S* is *small*. Thus *NB* stands for *negative big*, *PM* stands for *positive medium* and so on. Considering the dynamic behaviour, the spacing error and the characteristics of the PID controller, the adaptive Fuzzy-PID control gains are set as follows:

1. When the error is **large**, in order to speed up the response of the system and prevent the differential overflow that may be caused by a sudden rise at the beginning, a larger K_p and a smaller K_d should be selected. The integral function is too strong to increase the overshoot. Therefore, a smaller value of k_i.

2. When the error is **medium**, in order to reduce the overshoot of the system and to ensure a certain response speed, K_p should be appropriately reduced and the values of K_d and K_i should be low.

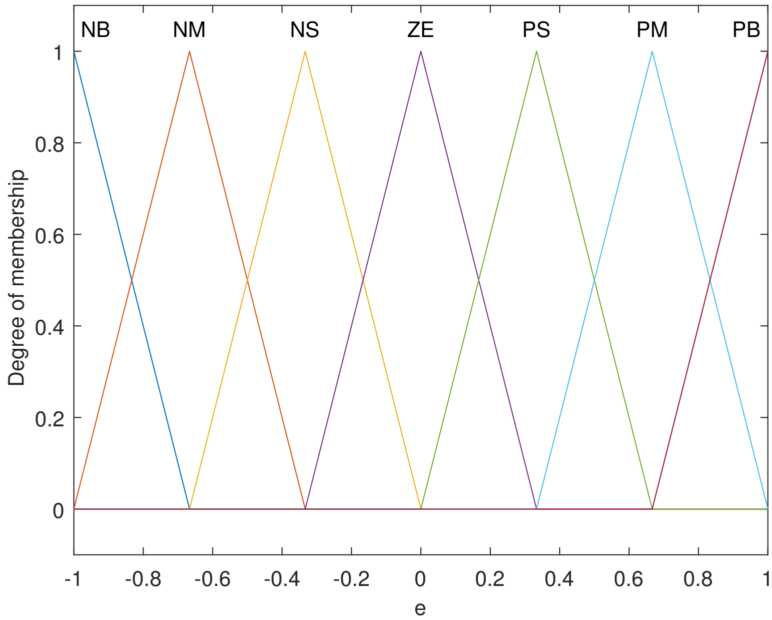


Fig. 4.4 Membership function

3. When the error is **small**, in order to reduce the steady-state error, K_p and K_i should be larger avoiding output response oscillation and maintaining the robustness of the system. Thus, K_d is chosen according to the absolute value of ec. If ec is large, K_d is set to a small value.

In Table 4.2[92], based on the e and ec, 49 fuzzy rules are stated. The outputs Δk_p, Δk_i, Δk_d are defined depending on the inputs e and ec. For example, first and second elements in the first column indicate the following:

1. If the inputs e and ec are NB and NB, respectively, the outputs Δk_p, Δk_i, Δk_d are PB, NB, PS.

2. If the inputs e and ec are NM and NB, respectively, the outputs Δk_p, Δk_i, Δk_d are PB, NB, PS.

Table 4.2 Fuzzy control rules of parameters Δk_p, Δk_i and Δk_d

	ec						
e	NB	NM	NS	Z	PS	PM	PB
NB	PB NB PS	PN NB NS	PM NM NB	PM NM NB	PS NS NB	Z Z NM	Z Z PS
NM	PB NB PS	PN NB NS	PM NM NB	PS NS NM	PS NS NM	Z Z NS	NS Z Z
NS	PM NB Z	PM NM NS	PM NS NM	PS NS NM	Z Z NS	NS PS NS	NS PS Z
Z	PM NM Z	PM NM NS	PS NS NS	Z Z NS	NS PS NS	NM PM NS	NM PM Z
PS	PS NM Z	PS NS Z	Z Z Z	NS PS Z	NS PS Z	NM PM Z	NM PB Z
PM	PS Z PB	Z Z PS	NS PS PS	NM PS PS	NM PM PS	NM PB PS	NB PB PB
PB	ZE ZE PB	ZE ZE PM	NM PS PM	NM PM PM	NM PM PS	NM PB PS	NB PB PB

4.6 Simulation results for fuzzy controller platoon system

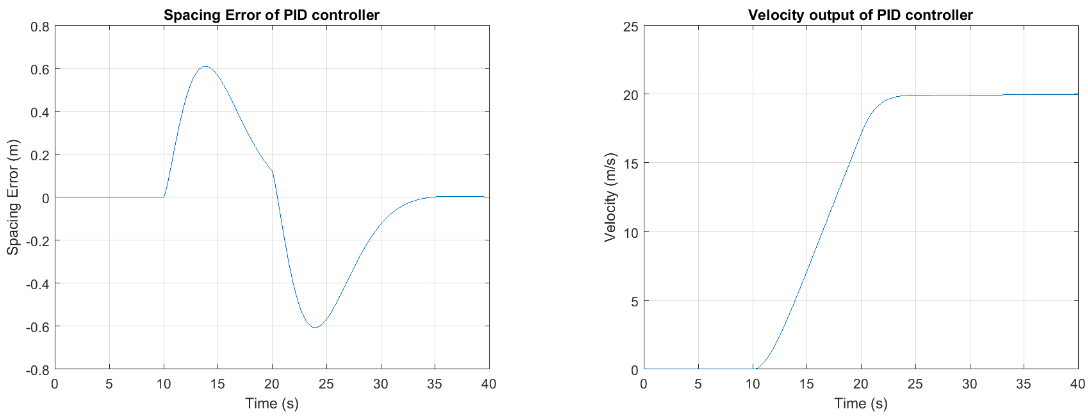
In the simulation, Matlab/Simulink was used to simulate an individual vehicle and the received velocity signal as input for the control. The output is the velocity of the vehicle. In the platoon system, the simulation used the output vehicle signal ahead of the input. Therefore, the communication was considered 100% reliable. The numerical simulations were used to present this vehicle-following system. Note that the initial position and velocity were both equal to zero. The velocity of the leading car was

$$v_0 = \begin{cases} 0m/s & \text{, if } t \leq 10s \\ 2tm/s & \text{, if } 10s < t \leq 20s \\ 20m/s & \text{, if } t > 20s \end{cases} \tag{4.38}$$

The main goal was to obtain the dynamic behaviour of the vehicle, which also considers the communication time delay. The delay is set to $\tau = 0.5$. When setting velocity from 10 to 20 s, its acceleration is $2m/s^2$. Firstly, the PID controller was designed to use the stability margin to calculate the control gains. The simulation used the parameters as follows to meet the stability requirements:

$$k_p = 2, k_i = 3, k_d = 0.5, h = 1.5 \tag{4.39}$$

By initialising the received velocity of the vehicle in front by the V2V communication, the performance of the traditional PID controller is shown in Fig.4.5. The spacing and velocity of the control goal in the CD policy are related in Equation 4.1. This thesis can produce the following results combined with Figure 4.3. The difference in displacement between the two vehicles is known as the spacing error. The derivative of the vehicle's displacement yields the speed result.



(a) Spacing error performance of PID controller (b) Velocity error performance of PID controller

Fig. 4.5 Platoon performance under PID controller

In Fig. 4.5, it's worth mentioning that the spacing error could be negative in this scenario. Because the distance is set to CTH policy as described in Equation 4.1. The difference between the set value and the actual distance of the two vehicles is expressed by the spacing error. If the distance between the two vehicles is negative in the actual, it signifies the two cars crashed, and there is no need for further debate. The range of the spacing error was roughly [-1,1] and the speed error was within [-0.5,0.5]. The proportion parameters of the fuzzy input were set to unity and the error rate was 0.5. The outputs of the fuzzy controller were the parameters of the PID controller. Considering Δk_p, Δk_i and Δk_d as the output of the fuzzy controller, the overall gains of the fuzzy-PID controller were

$$K_{p,i,d} = \Delta k_{p,d,d} + k_{p,i,d} \tag{4.40}$$

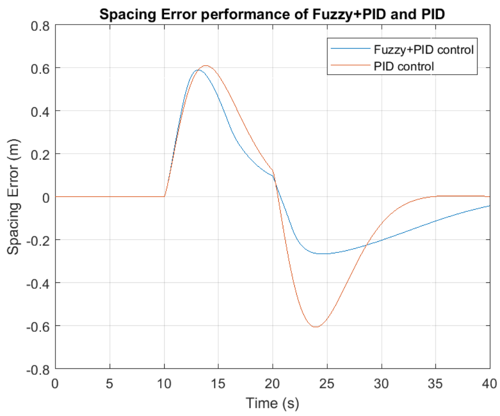
4.6.1 Car-following model simulation

This chapter uses the bound of the spacing error and the time to the target speed to evaluate the ability of the controller as [14] presented. Figure 4.6(a) clearly shows the spacing error difference between the conventional PID control and the improved fuzzy-PID control. In this figure, the error bound of the fuzzy-PID controller spacing error is -0.23 to 0.58 m and that of the conventional PID controller is -0.6 to 0.6 m. The fuzzy-PID controller has less spacing error in the upper and lower limits. Thus, the positive spacing error performance of the fuzzy control is slightly higher than the PID controller, but the negative spacing error is significantly better than the PID control. This implies that the control in the platoon vehicles system with the fuzzy controller was closer than that with the PID controller.

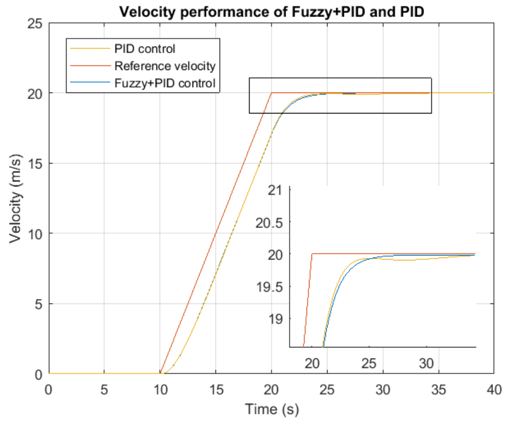
Fig.4.6(b) demonstrates the velocity of the different control methods. The fuzzy-PID controller had a shorter rise time and could meet the target speed rapidly. The PID controller took a longer time to reach the target speed. However, based on these figures, the fuzzy-PID controller also has drawbacks. The fuzzy controller has more fluctuation than the PID controller, but the adaptive controller has more potential since it can edit and fix the fuzzy rules using machine learning technology as needed.

4.6.2 Vehicle platoon system simulation

The fuzzy-PID controller was then applied to the vehicular platoon system. Based on the designed car-following system, the experiment moves to a further step. It is noted, the vehicle could only obtain the dynamic vehicle information of the vehicle in front. The experiment was designed for a four-vehicles platoon system. Figs.4.8(a) and 4.7(a) show the spacing error between neighbouring vehicles as a function of time. As the error passed through the platoon, the spacing error attenuated each time for both controllers. The two figures indicate



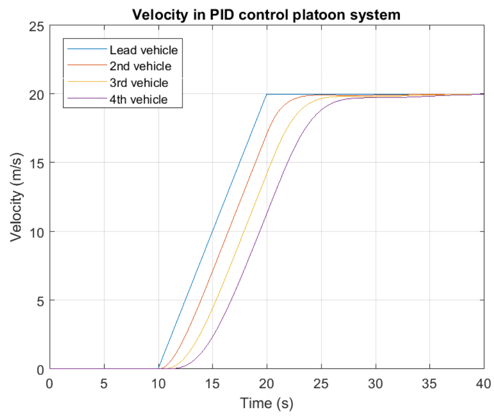
(a) Spacing error performance of Fuzzy-PID controller



(b) Velocity error performance of Fuzzy-PID controller

Fig. 4.6 Platoon performance under Fuzzy-PID controller

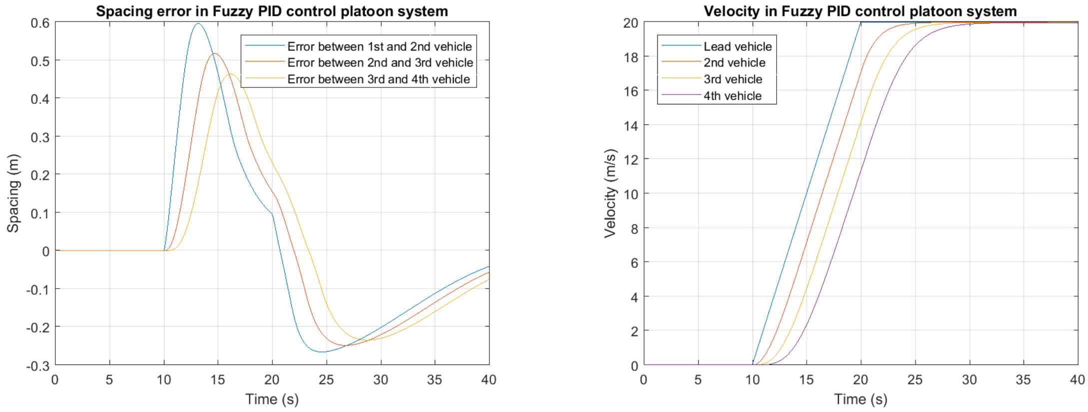
(a) Spacing error performance of PID controller



(b) Velocity performance of PID controller

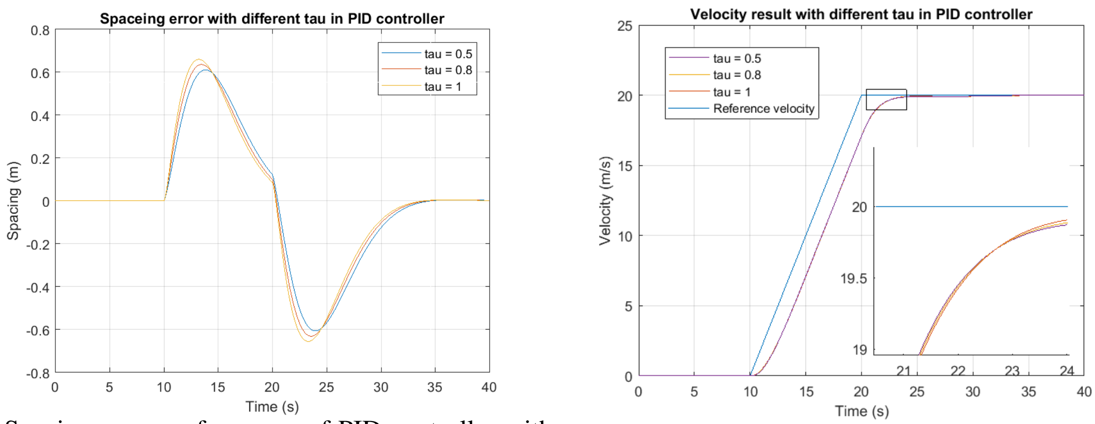
Fig. 4.7 Platoon performance of PID controller

that the two controllers maintained the characteristics of the car-following system, which is in the negative spacing error and the new controller outperformed the original controller. The results show that the time-gap constant h had to satisfy $h > 2\tau$ to maintain string stability. Figs.4.8(b) and 4.7(b) illustrate the velocity from the lead vehicle to the fourth vehicle. The conclusion, though not particularly clear in these figures is that the oscillation of the new controller was smaller. Therefore, in a real vehicle platoon, the spacing error will decrease more than with the PID controller, which will increase the traffic efficiency.



(a) Spacing error performance of fuzzy-PID controller (b) Velocity error performance of fuzzy-PID controller

Fig. 4.8 Platoon performance of fuzzy-PID controller



(a) Spacing error performance of PID controller with different τ

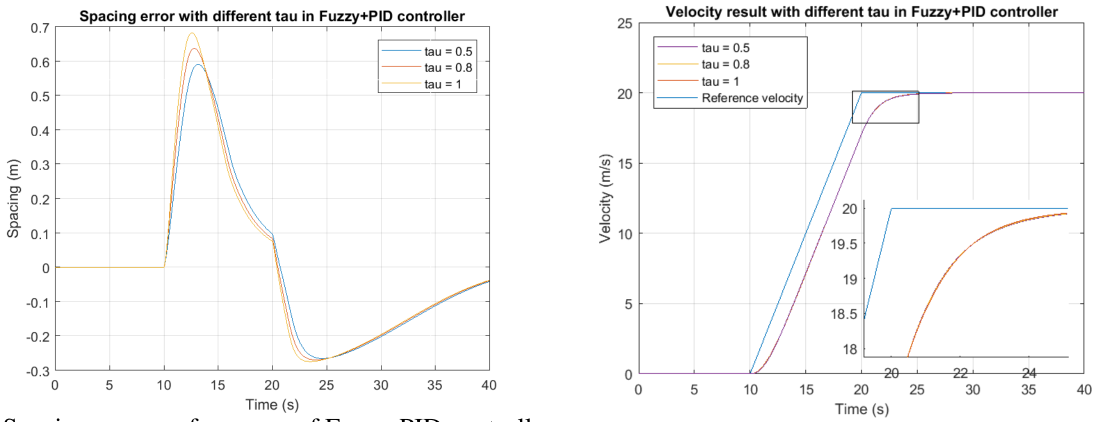
(b) Velocity performance of PID controller with different τ

Fig. 4.9 Platoon performance of PID controller with different τ

4.6.3 Features and effects of the proposed fuzzy controller

Vehicle parameter τ in the vehicle platoon system

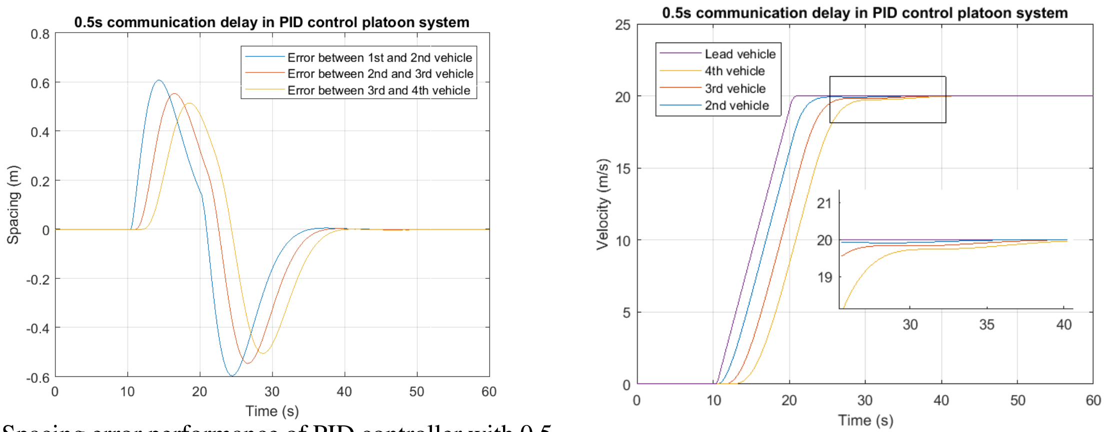
Figures 4.9 and 4.10 show the spacing error and velocity performance under the PID controller and the fuzzy-PID controller. In the spacing error under different vehicle parameter τ, the fuzzy-PID–controlled platoon system had an overall smaller error band. The spacing error increases, as τ increases, indicating the node vehicle in the platoon system was difficult to control. In the negative spacing error of Fig.4.10(a), τ had little effect on the whole system. In the velocity cooperation, the PID controller required more setting time and exhibited



(a) Spacing error performance of Fuzzy-PID controller with different τ

(b) Velocity performance of Fuzzy-PID controller with different τ

Fig. 4.10 Platoon performance of Fuzzy-PID controller with different τ



(a) Spacing error performance of PID controller with 0.5 s delay

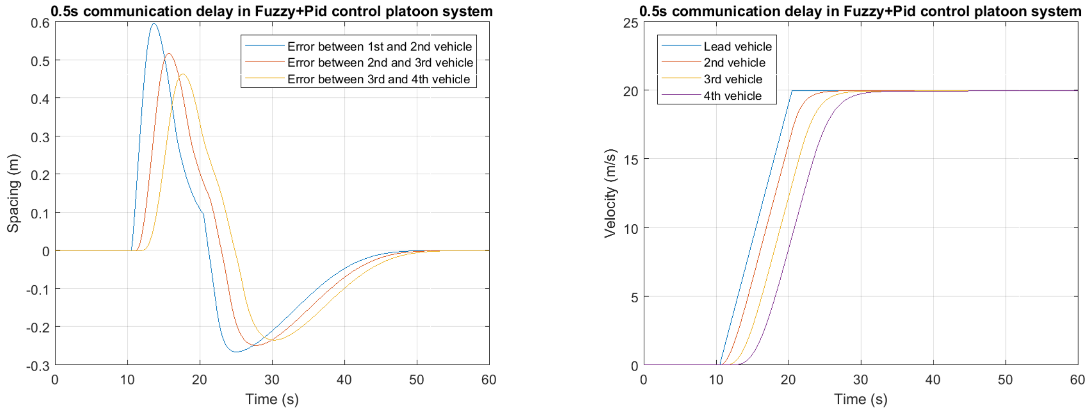
(b) Velocity performance of PID controller with 0.5 s delay

Fig. 4.11 Platoon performance of PID controller with 0.5 s delay

fluctuation. Also, the fuzzy logic control had less effect with the vehicle parameter, saving energy of the vehicle platoon system. In summary, the fuzzy logic controller in the platoon system had less impact on the vehicle dynamic parameter compared with the original PID controller.

Consistent communication delay

Figures 4.11 and 4.12 show the spacing error and velocity performance under PID and fuzzy-PID control with a constant 0.5-s communication delay in a four-car platoon system.



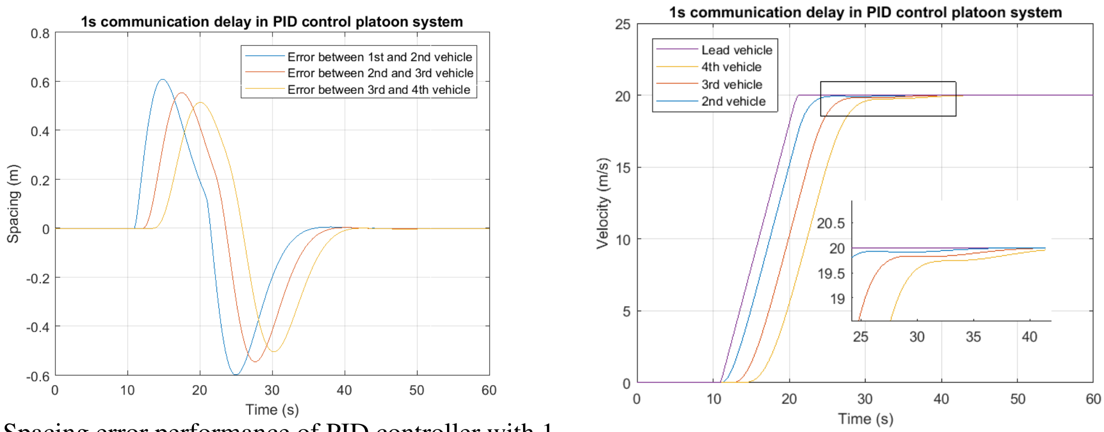
(a) Spacing error performance of fuzzy-PID controller with 0.5 s delay

(b) Velocity performance of fuzzy-PID controller with 0.5 s delay

Fig. 4.12 Platoon performance of fuzzy-PID controller with 0.5 s delay

With the same communication, the spacing error decreased through the platoon, indicating string stability. This simulation sets the communication t = 0.5 and1 s, as [62] set. However, the latency of the main V2V communication methods is usually on the order of hundredths of a second (10^{-2} s), such as IEEE802.11P vehicular networks [23]. In this area of study, the researchers would like to set a larger communication to test the algorithm. The fuzzy-PID controller had less error band with the communication delay, which was from -0.27 to 0.6 m vs -0.6 to 0.6m. As the previous results have shown, the maximum absolute value of the negative spacing errors of the fuzzy-PID controller was significantly reduced. In Figs. 4.12 (b) and 4.11 (b), the classification of the communication delay effects of the different controllers was challenging. However, the following car had a longer response time than the platoon without a communication delay, which is reason that invested in the development of communication technology to reduce and eliminate communication delays.

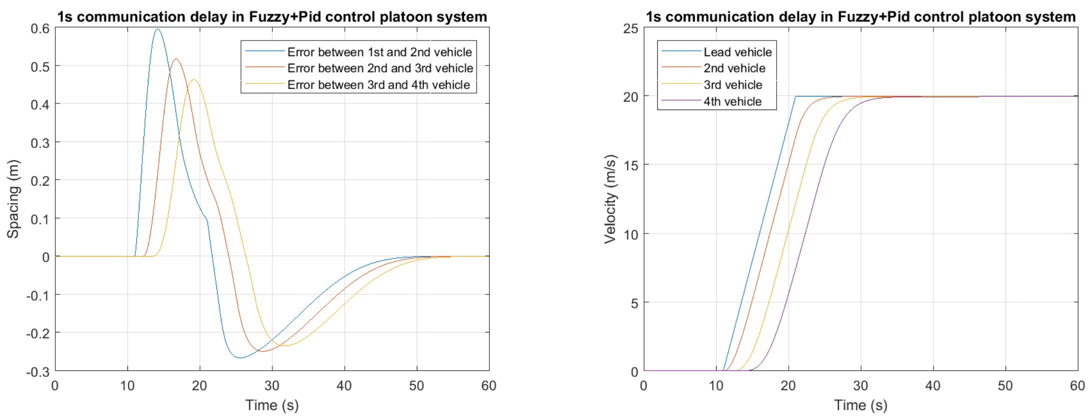
Figures 4.13 and 4.14 shows the four-car platoon under the PID control and proposed fuzzy-PID control with a 1-s communication delay. In the spacing error figures, the blue, red and yellow curves show the errors between first and second vehicles, second and third vehicles and third and fourth vehicles, respectively. The conclusion from these figures is similar to the above. However, with the longer communication delay, the setting times for both controllers were longer compared with 0.5-s communication delay. Therefore, the



(a) Spacing error performance of PID controller with 1 s delay

(b) Velocity performance of PID controller with 1 s delay

Fig. 4.13 Platoon performance of PID controller with 1 s delay



(a) Spacing error performance of fuzzy-PID controller with 1 s delay

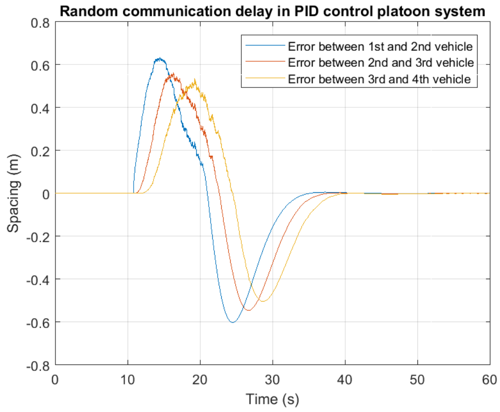
(b) Velocity performance of fuzzy-PID controller with 1 s delay

Fig. 4.14 Platoon performance of fuzzy-PID controller with 1 s delay

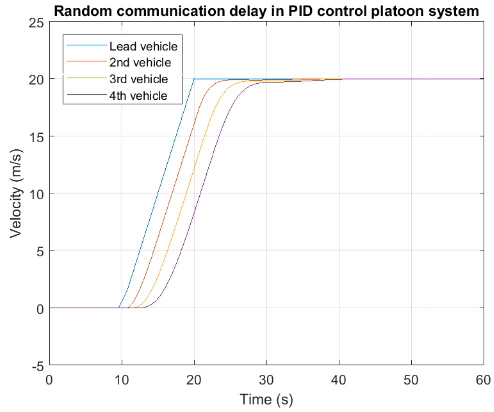
communication delays consumed too much control and were detrimental to the effectiveness and quality of the vehicular platoon system.

Random communication delay

In the real scenario, the communication delay is not constant. This simulation sets the noise $n(t)$ to be a uniformly distributed series of numbers between zero and one, i.e. $n(t)$ N(-0.5,0.5) and the sampling time to $T_s = 0.1s$. Figures4.15 and 4.16 show the four-car platoon system with the communication delay T_d. The overall communication delay fluctuated by

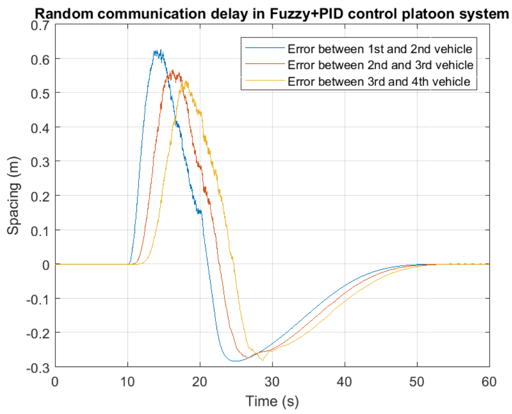


(a) Spacing error performance with random delay

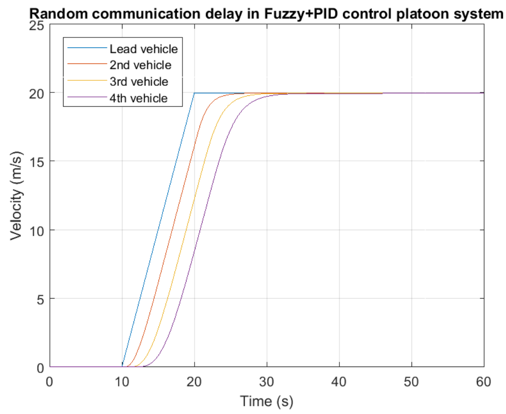


(b) Velocity performance with random delay

Fig. 4.15 Platoon performance of PID controller with random delay



(a) Spacing error performance with random delay



(b) Velocity performance with random delay

Fig. 4.16 Platoon performance of fuzzy-PID controller with random delay

0.5 s per the following equation:

$$T_d = T_c + n(t) \tag{4.41}$$

where T_c is the constant communication delay of 0.5 s. Different from the previous figures, the curves exhibit fluctuation, showing the communication delay effect on this vehicular platoon system. With this communication delay, the entire system still converged along the platoon, indicating string stability. The distances between the vehicles were small after that (see the red and yellow curves in these figures). If the uncertainty of communication delay increased, the entire system would lose string stability. In reality, this phenomenon may be inconvenient the driver and passenger. However, the velocity response does not indicate this because the simulation is on a highway with a constant speed.

In the case of stable speed, the influence of communication delay is usually not significant. The platoon system just requires the controller to maintain this speed. With the effect of the communication delay, the comparison of these two controllers is similar to the previous conclusion. The error band of the fuzzy-PID controller was less than that of the PID controller, especially with the negative inter-vehicle spacing error in which the fuzzy-PID controller performance outperforms the PID controller. In the velocity figures, the result is similar to Fig.4.13(b), exhibiting small floating, a disadvantage of PID control.

4.6.4 Heterogeneous vehicular platoon under the proposed controller

This section assumed a complex scenario with the vehicular platoon system. In addition to the vehicle platoon described above, cutting edge studies and CACC urgently depend on the suspicion of vehicle-autonomous driveline dynamics (homogeneous platoon) [127]. In reality, the characteristics vary among vehicles. Therefore, a vehicle platoon composed of different types of vehicles is called heterogeneous vehicle platoon (HVP) [128]. In this model, the HVP can be described as node vehicles with different parameters, i.e. τ_i, where i is the vehicle order in the platooning. The simulation coefficients can be set per Table 4.3:

Utilising these set parameters in Matlab/Simulink, the simulation results are demonstrated in Fig.4.17.

In this experiment, the goal was to test how the proposed controller works in an HPV. The lead vehicle transferred dynamic information to the second vehicle with the floating noise. The second vehicle transferred dynamic information to the third vehicle, etc. In Fig.4.17, the blue curve fluctuates violently because the signal from the reference lead vehicle was transmitted to the second vehicle with noise and as uncontrolled dynamic data. The spacing error and velocity response of the following vehicles were smooth with the effect of control. In summary, the proposed fuzzy-PID controller had a filtering effect. In other words, this controller was not sensitive to the changing of velocity. The inter-vehicle spacing indicates

Table 4.3 Simulation parameters

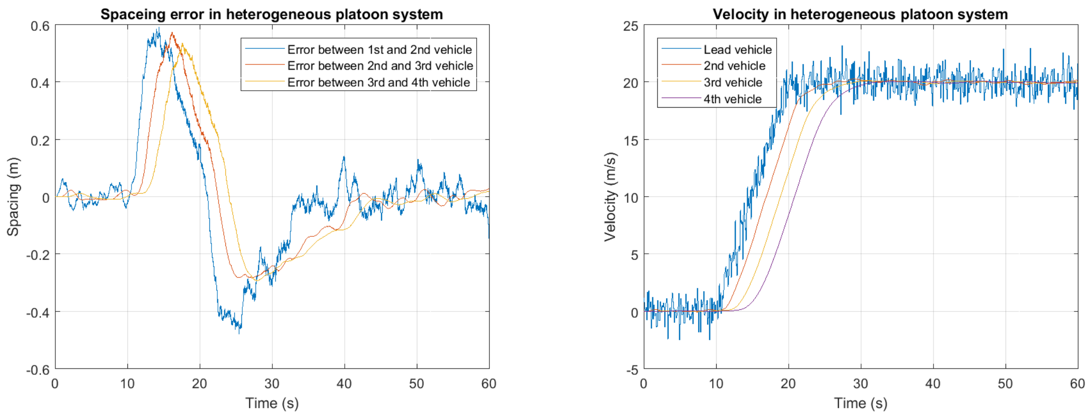
Parameters	Value
Ref(τ_1)	Equation 4.38
τ_2	0.5
τ_3	0.8
τ_4	1
T_d	(0,1) s
T_s	0.1 s

that if the communication in the V2V communication was unstable, stability was difficult for the vehicle platoon.

Comments on τ. This test has a profound comprehension of the role of τ in the node vehicle model. It expresses the absolute time from when the entire node vehicle receives the signal to when the vehicle dynamic data (acceleration and velocity) matches this signal. As mentioned in [24], this is called a "lumped" delay. This delay includes the aerodynamic delay, mechanical delay, road friction delay and communication delay. This thesis focused on the communication delay separately to assess the influence of communication delay on the designed controller.

4.7 Summary

In summary, a novel fuzzy-PID controller with V2V communication was designed for a car-following system and vehicular platoon system. The closed-loop stability and string stability was verified using the Routh-Hurwitz and polynomial methods. With the stability margin, the designer can easily choose the parameter values in the controller. The experimental results prove that this method met the modern control requirements of the vehicle platoon systems and the distance between the vehicles gradually attenuated in the direction of the



(a) Spacing error in heterogeneous platoon system

(b) Velocity in heterogeneous platoon system

Fig. 4.17 Heterogeneous platoon performance of fuzzy-PID controller with random delay

platooning, indicating that string stability was maintained. Then, it studied the influence of communication delay on the designed controller. This controller maintained superior characteristics than traditional a PID controller. Especially in the negative inter-vehicle spacing error, performance exceeded the PID controller. In the study of node vehicle parameter τ with the proposed controller, a larger τ value caused difficulty in vehicle control. Finally, the fuzzy-PID controller had a filtering effect when tested in the HPV. If the delay changed considerably, the system lost stability. Therefore, the string stability and communication stability of the designed controller are two vital conditions for achieving an effective vehicle platoon. In future research, neural network technology in the fuzzy logic control can be applied to change the fuzzy rules. Additional communication topologies can be studied with the fuzzy-PID controller.

Although the CTH approach can improve the vehicular platoon safety, with the demand for greater transportation efficiency concern, the CD approach can increase traffic flow and, as a result, can improve transportation efficiency. Therefore, the main challenge of the controller is safety. With the powerful tool of V2V communication, a whole platoon controlled by the master controller becomes possible. In the next chapter, the SMC controller with the V2V communication is demonstrated. This novel method in the TEV project can ensure both efficiency and safety at high speed.

Chapter 5

Slide Model Control with Globe Information for Constant Distance Control

Vehicle platoon systems are widely recognized as a key enabler to address mass-transport. V2V and V2I are two technologies that drive platooning, where vehicle distance and velocity are two main important parameters that must be controlled either by using linear or non-linear control. In my thesis, a new mass-transport system has been proposed, called TEV. In TEV, the inter-vehicular distance is reduced to only a quarter of the regular car length and cars drive at 200km/h enabling mass transport at speed as the introduction. However, conventional linear and non-linear controllers fail to control each vehicle at these scenarios. Lately Sliding Mode Control has been applied to control platoons but only for inter-vehicular distance that is greater than 1 car length and at low speed. This chapter investigates the use of SMC for TEV. It studies different V2V communication topology structures using graph theory and proposes a novel SMC design with and without global dynamic information. It is shown that node vehicle stability and string stability cannot be ignored so the Lyapunov candidate function was chosen to study the impact which forms an integral part for future research.

5.1 Constant Distance Modelling

First of all, as the main modelling method in this thesis, it is important to discuss the formation geometry. The main control target is maintaining the desired space and velocity consistency. When using a CD policy, it is important to maintain a small but safe distance, hence it can achieve higher traffic efficiency. In the CTH policy the distance follows a linear relationship with self-velocity; somehow it is similar to a driver's behavior but the distance between the two vehicles is larger. As a result, it cannot deliver efficiency as high as the CD policy, however, it is safer than using the CD policy if the communication can not be trusted. In this chapter, for efficiency concerns it uses CD policy.

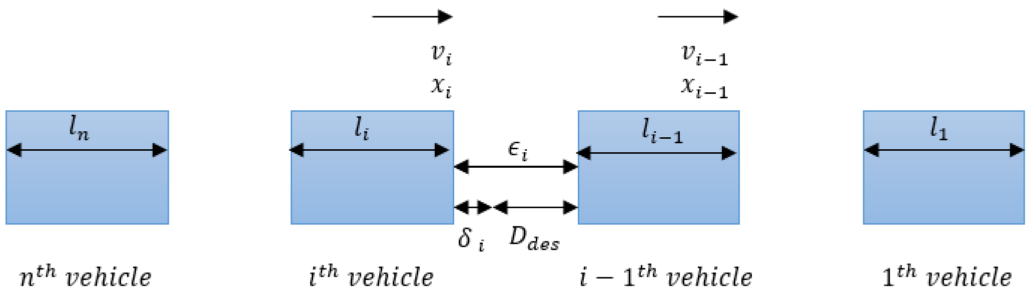


Fig. 5.1 Vehicles platoon system geometry

As Fig.5.1 shows, the inter-vehicular spacing is defined as:

$$\varepsilon_i = x_{i-1} - x_i - l_{i-1} \tag{5.1}$$

where ε is the inter-vehicular spacing, x_i and x_{i-1} are the vehicle head position for vehicle i and vehicle $i-1$; l_{i-1} is the vehicle length of vehicle i_1. Then the spacing error for vehicle i can be defined as:

$$\delta_i = D_{des} - \varepsilon_i \tag{5.2}$$

where D_{des} is the desired spacing between vehicles and δ_i is the spacing error of the vehicle i.

5.2 Slide Model Controller design

As explained in the introduction, SMC controllers have recently been applied to vehicle platooning in this chapter.

5.2.1 SMC Control with Lead Vehicle Information (Classical Method)

Now, with the help of V2V communication, it gives the possibility of the position, velocity and acceleration to be broadcast from any neighboring vehicles. Hedrick [82] defines a typical slide surface S_i that combines the dynamic information with the lead and preceding vehicles. In this chapter, the slide surface has changed to the following equation:

$$\begin{aligned} S_i = & q_1\dot{\delta}_i + q_2\delta_i + q_3(\dot{x}_i - \dot{x}_0) \\ & + q_4(x_i - x_0 + \sum_{j=1}^{i} d_{j,des}) \end{aligned} \tag{5.3}$$

where S_i is the ith vehicle slide surface in the platoon system, $\dot{\delta}_i$ is the velocity error of the ith vehicle with respect to its preceding vehicle, $d_{j,des}$ is the fixed distance from vehicle i to the leading vehicle, q_1, q_2, q_3 and q_4 are the coefficients for the slide-controller. It is assumed that the length of each vehicle has been ignored. The reaching law for the vehicle in the platoon system can be designed as:

$$\dot{S}_i = -\lambda S_i \tag{5.4}$$

where $\lambda > 0$ is a turning parameter. It is used in equation 5.3 and 5.4 to calculate the input of each vehicle in the platoon system. Note that the input u_i is equal to $\ddot{x}_i$ in the following equation:

$$\begin{aligned} u_i = & \frac{1}{q_1 + q_3}[q_1\ddot{x}_{i-1} + q_3\ddot{x}_0 - (q_2 + \lambda q_1)\dot{\delta}_i - (q_4 + \lambda q_3) \\ & \cdot (\dot{x}_i - \dot{x}_0) - \lambda q_2\delta_i - \lambda q_4(x_i - x_0 + \sum_{j=1}^{i} d_{j,des})] \end{aligned} \tag{5.5}$$

where x_0, $\dot{x}_0$ and $\ddot{x}_0$ are the dynamic information of the lead vehicle, δ_i is the spacing error between the ith vehicle and the $i-1$th vehicle. Using equations 5.3 and 5.5 numerical simulations for the platooning system can be performed and this is shown in the next section. If it uses the signal vehicle model, it means one must consider the actuator and communication lags, which then changes to:

$$\tau_i \frac{d}{dt}\dot{u}_i + u_i = u_{il} \tag{5.6}$$

where u_{il} stands for the input with 'lumped' lags for vehicles. It now needs to analyze the stability of this controller in next section.

5.2.2 SMC Control with Global Information (Proposed Method)

Graph theory was introduced in chapter 3 and SMC can use this as a mathematical way to describe different communication structures. The proposed method to design a SMC is detailed in this chapter. So the idea of the proposed controller is to make the system converge to the sliding surface $s_i = 0$ as soon as possible. Then it can consider the system's stability of string stability such that $s_i = s_{i-1} = 0$. The SMC with the lead vehicle information can be designed in two steps: Step 1, Sliding surface design, which depends on the types of error involved and Step 2, The reaching law design, which must be able to reach the slide surface quickly and makes sure there is no chattering effect near the surface. Hence with the elements a_{ij} and p_i from the leader adjacency matrix and adjacency matrix, equation (5.3) becomes:

$$\begin{aligned} s_i(t) = &\sum_{j=1, j\neq 1}^{N} a_{ij}(\dot{\delta}_{i,j} + (x_i - x_j + \sum_{k=1}^{|j-i|} d_{k,des})) \\ &+ p_i((\dot{x}_i - \dot{x}_0) + (x_i - x_0 + \sum_{k=1}^{i} d_{k,des})) \end{aligned} \tag{5.7}$$

To simplify equation 5.7 sets:

$$\Delta x_i = x_i - x_0 + iD_{des} \tag{5.8}$$

Now equation 5.7 can be rewritten as:

$$s_i(t) = \sum_{j=1, j\neq 1}^{N} a_{ij}(\dot{\delta}_{i,j} + (\Delta x_i - \Delta x_j)) + p_i(\dot{\delta}_{i,0} + \Delta x_i) \tag{5.9}$$

It can now define a relationship between velocity error and spacing error which is:

$$\dot{\delta}_{i,j} = -\lambda_1(\Delta x_i - \Delta x_j) = -\lambda_1 \delta_{i,j} \tag{5.10}$$

Then equation 5.9 becomes

$$s_i(t) = \sum_{j=1, j\neq 1}^{N} a_{ij}(1-\lambda_1)\delta_{i,j} + p_i(1-\lambda_1)\delta_{i,0} \tag{5.11}$$

This the design of the slide surface for both the classical controller and the proposed controller which will use the communication topology matrix in next section.

5.3 Communication Topology Design in Platoon System

As the graph theory and communication topology matrix has been introduced in chapter 3, this section uses the communication topology matrix $L+P$ it obtains the platoon system sliding surface:

$$S(t) = \begin{bmatrix} s_1(t) \\ s_2(t) \\ \vdots \\ s_N(t) \end{bmatrix} = (1-\lambda_1)(L+P) \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \vdots \\ \Delta x_N \end{bmatrix} \tag{5.12}$$

Then, the next step to design a topology SMC for a platoon system is the reaching law. The task here is to enable the system to enter the sliding surface in any state for a limited time and to reach the desired performance. Now there are several reaching laws for a designer to choose from, such as constant reaching law, exponential reaching law or power reaching law. In this system it chooses the exponential reaching law which has less parameters to be set and quick response time. Then it can change the equation 5.4 to the topology SMC slide reaching law, which is:

$$\dot{s}_i(t) = -ks_i(t) \tag{5.13}$$

where the value of $k > 0$. Then the collective topological approach law becomes:

$$\dot{S}(t) = \begin{bmatrix} \dot{s}_1(t) \\ \\ \dot{s}_2(t) \\ \\ \vdots \\ \\ \dot{s}_N(t) \end{bmatrix} = -(1-\lambda_1)(L+P)\cdot kS(t) \tag{5.14}$$

If it takes the derivative of 5.12 and compare it with 5.14 it gives the full rank matrix. It can cancel $(1-\lambda_1)(L+P)$, so:

$$\begin{bmatrix} \Delta\dot{x}_1(t) \\ \\ \Delta\dot{x}_2(t) \\ \\ \vdots \\ \\ \Delta\dot{x}_N(t) \end{bmatrix} = -kS(t) \tag{5.15}$$

If it considers an individual vehicle control mode, the equation becomes:

$$\Delta\dot{x}_i = -ks_i(t) \tag{5.16}$$

By comparing the derivative of 5.6 with 5.16 it can obtain the input of the controller, which is:

$$u_{il} = \tau_i \dddot{x}_0 + \ddot{x}_0 + k^2(\tau_i + 1)s_i(t) \tag{5.17}$$

5.4 Stability Verification

5.4.1 Stability Study for Classical SMC

The proof for the classical SMC uses the polynomial method and the string stability polynomial can be used to calculate the stability margin. Moreover, the transfer function $\widehat{H}(s)$ for the error propagating in the platoon has to be bounded to a constant α. In this case, in order to construct the transfer function for spacing error it can use $S_i(s) - S_{i-1}(s)$ in s-domain, such that,

$$\begin{aligned}\Delta_i(s) =& \frac{q_1 s + q_2}{(q_1+q_3)s + q_2 + q_4}\Delta_{i-1}(s) \\ &+ \frac{(S_i(s) - S_{i-1}(s)) + (q_1+q_3)\delta_i(0) - \delta_{i-1}(0)}{(q_1+q_3)s + q_2 + q_4}\end{aligned}$$

If $t \to \infty$, it can obtain the string stability polynomial which,

$$z = \frac{q_2}{q_2 + q_4}$$

Therefore, while considering the coefficients design, it must satisfy:

$$\frac{q_2}{q_2 + q_4} < 1$$

From these equations it can be known that q_1 is independent of string stability. Now the stability polynomial method has successfully used to calculate the parameters relationship.

However, for a complex system which contains the information from multiply vehicles (more than 2), it is hard to use this method to analysis. So it uses the topology Lyapunov method in this case.

5.4.2 Stability Study for the Proposed SMC

As explained before, it is difficult to use the string stability polynomial to analyze stability in the topology platoon system. Thus, consider a platoon system with 2 preceding vehicles as the lead vehicles so the string stability polynomial is:

$$\|\delta_i\|_\infty = \alpha_1 \|\delta_{i-1}\|_\infty + \alpha_2 \|\delta_{i-2}\|_\infty$$

If the preceding lead vehicles become N as a result, the polynomial will have N items. It needs to analyze the stability by considering different situations and topology structures. To circumvent this problem researchers have used the Lyapunov method. In a typical sliding mode control the stability analysis has been separated into two parts, which are: reaching law stability and sliding surface stability.

Reaching Law Stability

The Lyapunov candidate for the topology platoon system is:

$$V(t) = \frac{1}{2} S(t)^T S(t) \tag{5.18}$$

The derivative of the Lyapunov candidate equation is:

$$\dot{V}(t) = -S^T(t)(L+P)kS(t) \tag{5.19}$$

From the graph theory $L+P$ is positive . So, it has the property that $x^T(L+P)x > 0$. Due to this, $\dot{V}(t)$ is negative $(S(t) \neq 0, \dot{V}(t) < 0)$. So, when $t \to \infty$, $S(t)$ moves towards zero $(S(t) \to 0)$. This shows that this surface can be reached asymptotically.

Sliding Surface Stability

Sliding surface stability chooses the Lyapunov candidate individual vehicle function as:

$$V_i = \frac{1}{2}\delta_{i,j}^2 \tag{5.20}$$

which is clearly positive. By taking the derivative of equation 5.20 obtains:

$$\dot{V}_i = \delta_{i,j}\dot{\delta}_{i,j} = -\lambda\,\delta_{i,j}^2 \tag{5.21}$$

Now by choosing $\lambda > 0$, $\dot{V}_i$ become negative.

Thus, the proposed SMC controller is able to change the matrix into different topology structures by changing its elements to make it more flexible for various vehicle platooning applications. Additionally, the design parameters are fewer than those in the classical SMC method. Using global communication by adding V2V communication, the platoon size is expandable. Due to the obvious constraints in communication range within a platooning scenario, it becomes difficult for the vehicle at the end of a platoon to obtain the lead vehicle's information. To overcome this limitation, the proposed method allows the application of a potentially viable topology structure where vehicles other than the lead and rear vehicles can act as repeaters to their respective consecutive vehicles and pass on the desired information. Now the controller design and stability has been demonstrated. The next challenge is determining the parameters of the EVs. This work uses the system identification knowledge define τ of each vehicle in the signal vehicle model. It assumes that each vehicle parameter is relatively unchanged.

5.5 System Identification

In this work, it proposes the EVs that enter the TEV lane will undergo an acceleration of $2m/s^2$. This accelerating procedure is required to obtain output data from the vehicle. Then it adds a zero mean and 0.1 variance Gaussian white noise to the output data as mechanical noise. The vehicle dynamic model the typical signal vehicle model with τ=0.5. Fig.5.2 shows the input signal and the output signals with noise. As can be seen in the figure, the abscissa unit is 0.01s, which corresponds to the sample time of this thesis. The results afterwards also follow this horizontal axis. By using the MATLAB System Identification toolbox, it can predict the value of τ=0.4834s and the fitting rate is 87.74%.

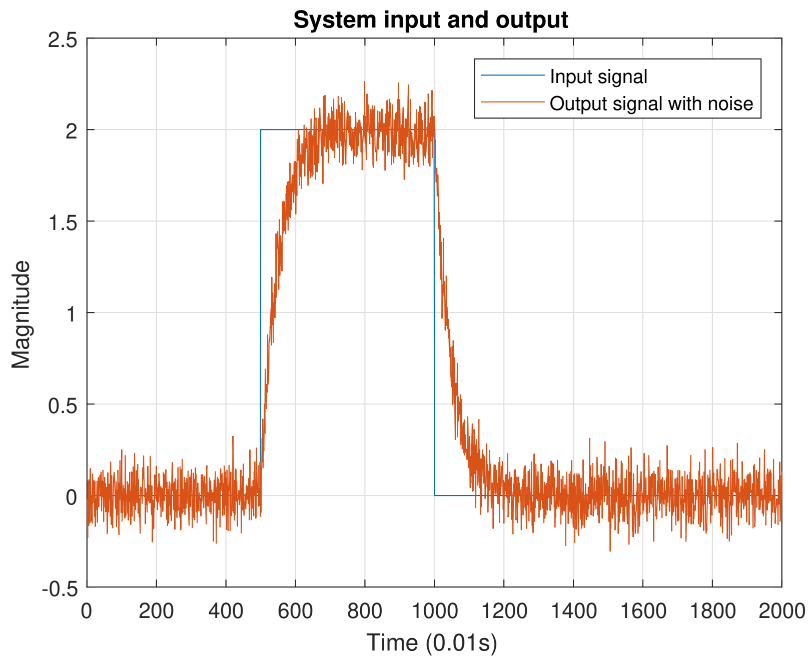


Fig. 5.2 System input and output signal

Fig.5.3 shows the measured value of the identification which is the red line in the upper figure. The black trace in the upper figure is the output from the tested vehicle which is the input of the identification system. The lower figure shows the error between input and output with a $\pm$0.2 magnitude. With this error the position error can be calculated within 0.05m which is too small to be ignored. So, in real time if the fitting rate can reach over 85% the error can be ignored in a platoon system. Now it has to set the vehicle models for the TEV lane. In simulation experimental, it uses the single vehicle model with these parameters to observe the output of the classical controller and the proposed SMC controller.

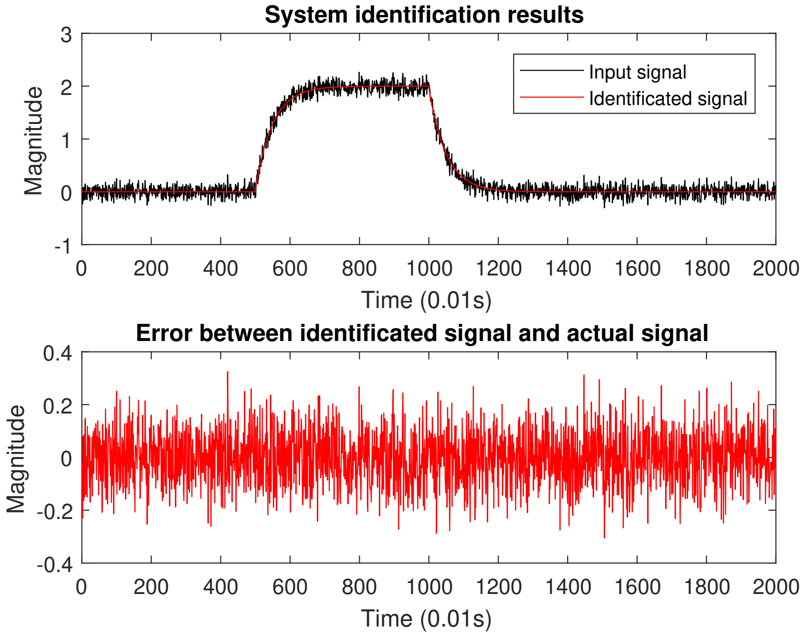


Fig. 5.3 System identification results

5.6 Simulation Results for Slide Model Control with Globe Information

This simulation has 10 vehicles forming one platoon all driving at a constant speed at $165.6km/h$ and all cars must reach $200km/h$ which is a TEV requirement. This platoon system is towed by a reference vehicle which is considered non-existent, thus it is a virtual vehicle as shown in Fig.5.4. The controller of this structure in Fig.5.4 uses the classical SMC. By contrast, the following simulation uses the proposed SMC controller with BD and BDL vehicular communication structure as shown in perviously. The platoon receives as disturbing signal of $+2m/s^2$ and $-2m/s^2$ to test its robustness and so they reach the upper speed of the TEV requirement. So, the acceleration of the reference vehicle a_r is:

$$a_r(t) = \begin{cases} 0 & 0s < t \geq 5s \\ 2 & 5s < t \geq 10s \\ 0 & 10s < t \geq 20s \\ -2 & 20s < t \geq 25s \\ 0 & t > 25s \end{cases} \tag{5.22}$$

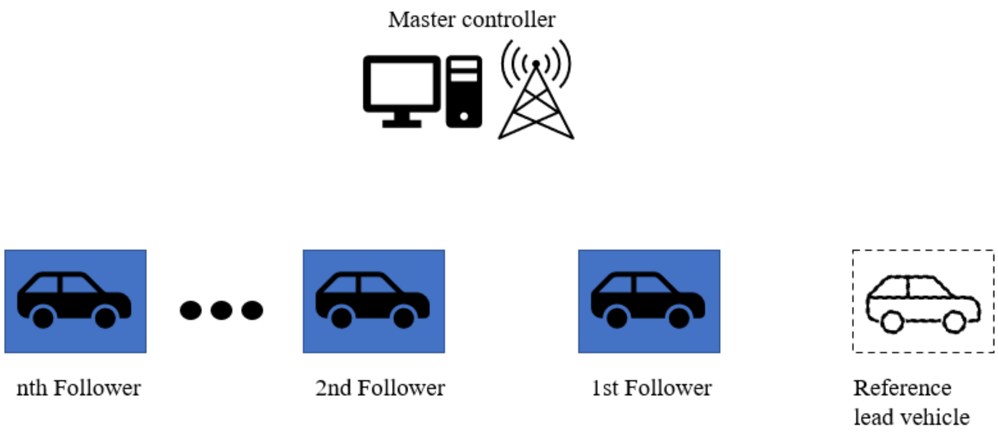
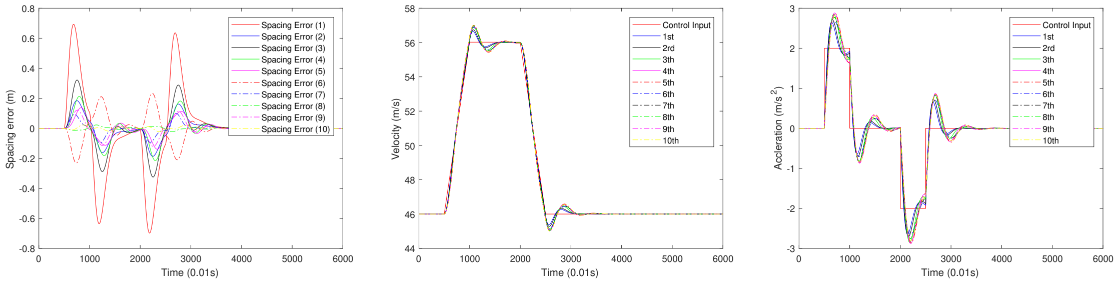


Fig. 5.4 Virtual lead vehicle

This section initializes the simulation parameters for the communication structure, velocity and spacing between vehicles. Note that, it assumes this is no errors between vehicles in the platoon system in the first place.

5.6.1 SMC Control with Lead Vehicle Information

In this experiment, each vehicle in the platoon system can receive the dynamic information for the reference lead vehicle and the vehicle in front this PLF structure which is shown earlier. This has been achieved by assuming all the vehicles have no initial spacing error, velocity error and acceleration error. Overall, to begin with all vehicles operate as normal in the TEV lane and the reference lead vehicle transmits signals as described in the piece-wise function shown in the piece-wise function 5.22.



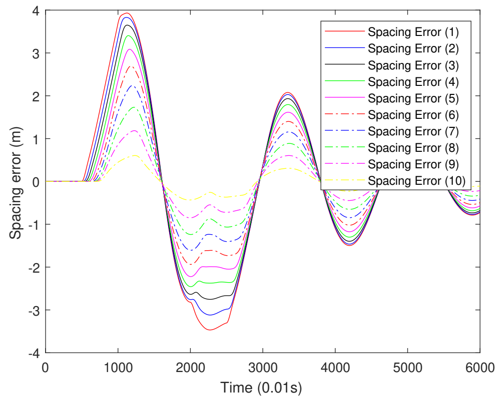
(a) Spacing error of the platoon system (b) Velocity of the platoon system (c) Acceleration of the platoon system

Fig. 5.5 Platoon system response

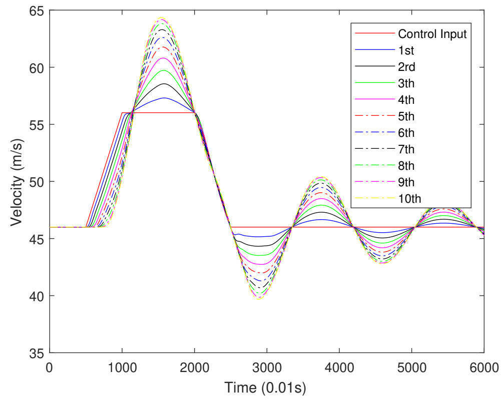
This controller is designed as shown in equation 5.4 with the parameter values: $q_1 = 1$, $q_2 = 3$, $q_3 = 2$, $q_4 = 1$ and $\lambda = 0.7$. The delay value τ of the reference lead value is 0.5. For other vehicles in the platoon system it assumes they have 10 similar random values distributed by the system. Figs.5.5 give the spacing error, velocity and acceleration respectively of the platoon system. The results of this controller in the platoon system has an approximate 0.5 error band, 5s settling time and an acceleration overshoot of nearly 50%. The spacing error and velocity for the platoon system are within the acceptable ranges. Note that the acceleration of the vehicle has an upper limit.

5.6.2 BD Structure for Platoon System

Fig.5.6 show the results of the BD communication structure for the platoon system. The node vehicle cannot obtain the lead vehicle's dynamic information directly as shown in this structure. It uses the model as shown in equation 5.17 and the parameters are set to: $\lambda_1 = 0.5$ and $k^2 = 6$. As a result, spacing error and velocity overshoot are higher than expected. The spacing error band is from about -3.5m to 4m and the velocity of the last vehicle can reach $230 km/h$ which is above the speed of $200 km/h$. Although the error will converge, the



(a) Spacing error of BD structure communication platoon system



(b) Vehicles velocity of BD structure communication platoon system

Fig. 5.6 BD structure platoon system response

settling time is too long. Thus, BD is not the best choice for a node vehicle to receive the dynamic information indirectly which will lead to a larger error and longer settling time.

5.6.3 BDL Structure for Platoon System

Now it can improve the BD structure by adding the lead reference vehicle's information to each node vehicle. Then this structure can be called the BDL structure. Before the simulation experiment, it uses the knowledge of algebraic graph theory to derive the matrix of the BDL communication topology. Under the BD topology, a vehicle can obtain the dynamic information of its preceding and following vehicles; while under the BDL topology, each following vehicle can also obtain information about the leading vehicle. So the adjacency matrix and the laplacian are:

$$(A_N)_{BD} = (A_N)_{BDL} = \begin{bmatrix} 0 & 1 & & \\ 1 & 0 & \ddots & \\ & \ddots & \ddots & 1 \\ & & 1 & 0 \end{bmatrix} \tag{5.23}$$

and,

$$(L_N)_{BD} = (L_N)_{BDL} = \begin{bmatrix} 1 & -1 & & \\ -1 & 2 & \ddots & \\ & \ddots & \ddots & -1 \\ & & -1 & 1 \end{bmatrix} \tag{5.24}$$

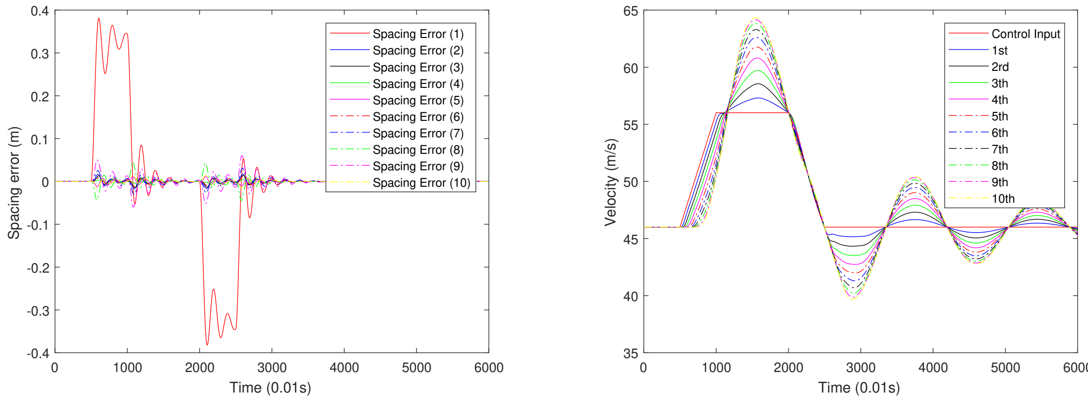
However, in the BD structure and BDL structure, whether the node vehicle can receive the information of the lead vehicle is different, so the adjacency sets $\mathbb{P}_i$ are different [19], so their adjacency matrices are respectively, which are:

$$(P)_{BD} = \begin{bmatrix} 1 & & & \\ & 0 & & \\ & & \ddots & \\ & & & 0 \end{bmatrix} \tag{5.25}$$

and,

$$(P)_{BDL} = \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & \ddots & \\ & & & 1 \end{bmatrix} \tag{5.26}$$

Now it utilizes the above matrix into the simulation experiment. The parameters and the model are the same as a BD structure experiment. Fig.5.7 demonstrate the results using BDL. The spacing error decreases significantly from the BD structure result. Moreover, the maximum velocity of the last vehicle is less than $205.2km/h$. From these results, it has successfully been shown that the BDL structure has improved the BD structure when the initial conditions are the same. A more significant and essential point is that gaining greater information from vehicles will lead to less spacing errors between vehicles.



(a) Spacing error of BDL structure platoon system (b) Vehicles velocity of BDL structure platoon system

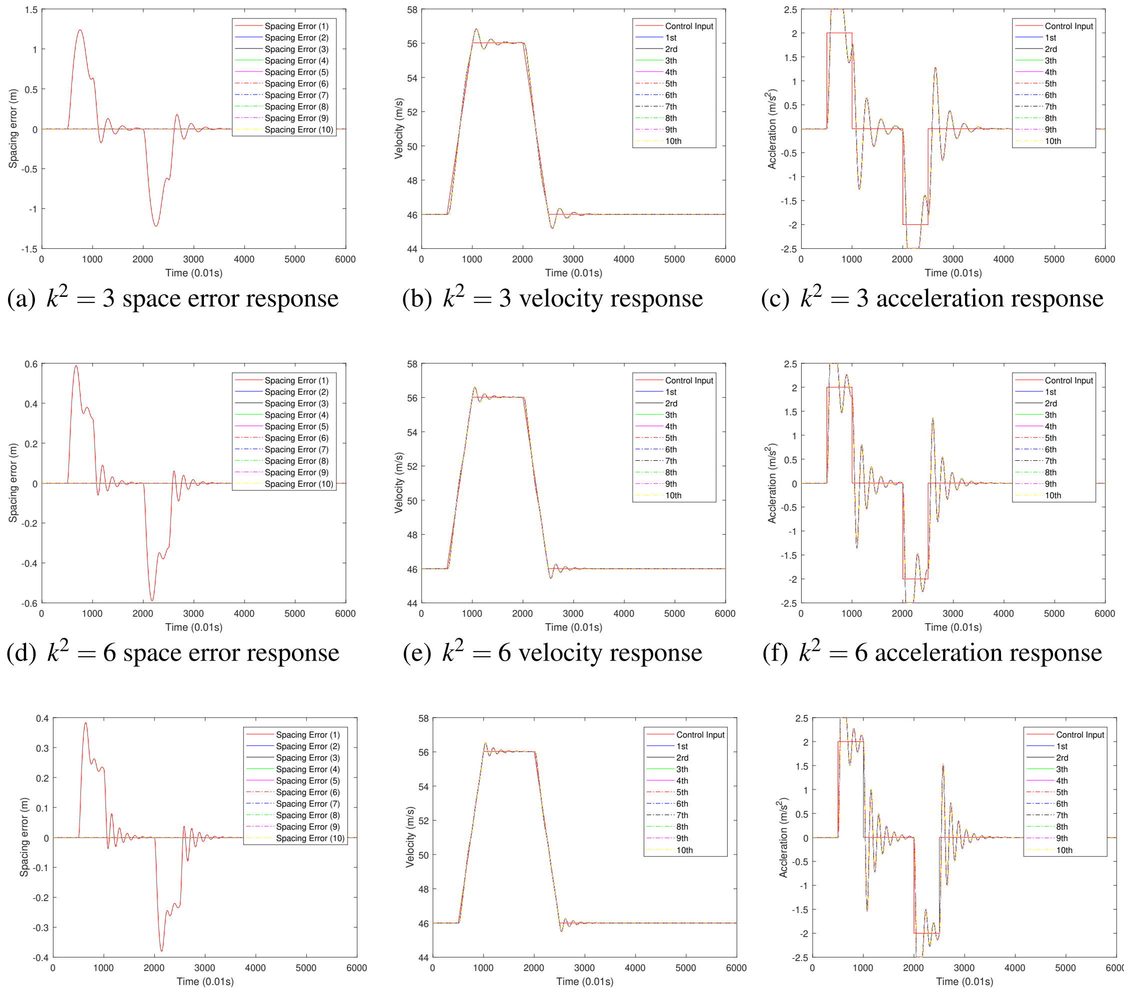
Fig. 5.7 BDL structure platoon system response

5.6.4 The features and effects of the proposed SMC

Fig.3.2 in Chapter 3 showed the corresponding matrices for typical BD and BDL platonic typologies, respectively. Their general structures can also be described using graph theory [14]. This means that the properties of the graph can be transformed into the properties of the corresponding matrix (eigenvalues, eigenvectors, etc.). Note that this description is only based on the topology structures between nodes and it does not consider communication characteristics, such as communication error, packet loss and delay. In the BD topology, the vehicle is capable of obtaining the information of its preceding and following vehicles. However, in the BDL topology structure, the following vehicle can also attain the information of the preceding vehicle. Therefore, This section applies the BDL structure for further research on the designed SMC with the parameters of controller k^2, the communication delay and vehicle parameter τ_i.

Controller coefficient k^2

The influence of the controller parameter on the distance was analysed between vehicles in the vehicle platoon, the vehicles' velocity and the acceleration of vehicles. It changes the parameter of the controller to k^2 = 3, 6, 9. The figures 5.8 are space error results, velocity results and acceleration results. It can be seen that as the k^2 increases, the space error in the



(a) $k^2 = 3$ space error response (b) $k^2 = 3$ velocity response (c) $k^2 = 3$ acceleration response

(d) $k^2 = 6$ space error response (e) $k^2 = 6$ velocity response (f) $k^2 = 6$ acceleration response

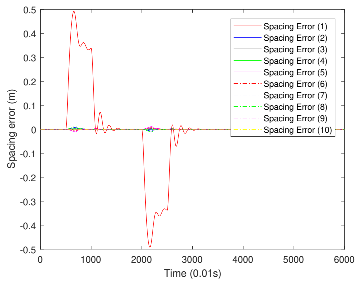
(g) $k^2 = 9$ space error response (h) $k^2 = 9$ velocity response (i) $k^2 = 9$ acceleration response

Fig. 5.8 The relationship between k^2 and the platoon system outputs

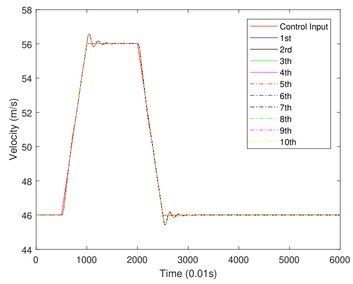
platoon system decreases. However, the oscillation of the acceleration of this system will increase significantly. So considering the oscillation and the space error, k^2 = 6 is an optimal choice.

Vehicle parameter τ_i

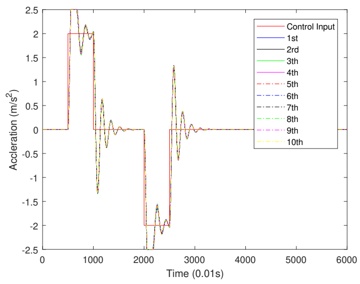
τ_i is the time delay constant of the vehicle longitudinal dynamic system. In fact, τ_i is the reaction time of the vehicle to the input signal. In the discussion above it chooses the k^2 = 6 and changed the value of τ_i to 0.4, 0.5, 0.6 with 0.01 variance Gaussian white noise. Fig.5.9 show the space error results, velocity results and acceleration results with respect to the different values of τ_i. From the results, it shows that with the increase of τ_i, the system will overshoot and oscillation of the space error, velocity and acceleration will increase. Therefore, the faster the vehicle's acceleration and deceleration respond, the smaller τ_i will be. Moreover, the τ_i corresponding to the acceleration and deceleration of the vehicle should be different. So in order to simulate the real-time situation, it will choose different τ_i to represent the vehicle acceleration time delay constant and vehicle deceleration time delay constant.



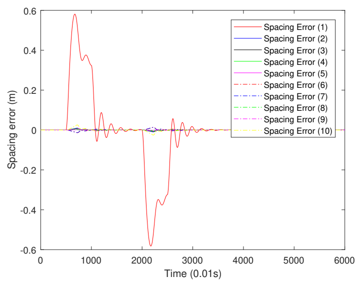
(a) $\tau_i = 0.4$ spacing error response



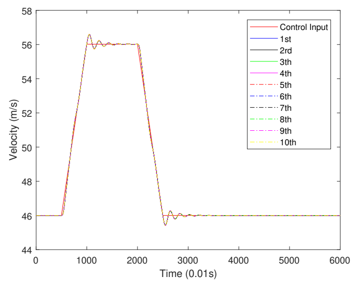
(b) $\tau_i = 0.4$ velocity response



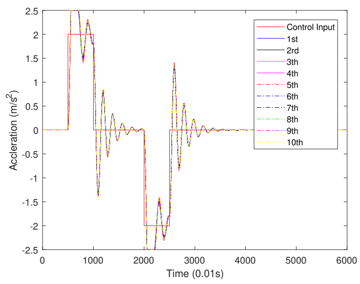
(c) $\tau_i = 0.4$ acceleration response



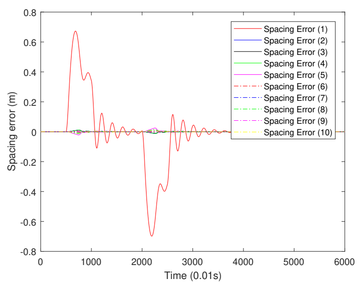
(d) $\tau_i = 0.5$ spacing error response



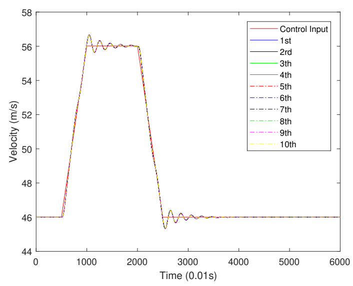
(e) $\tau_i = 0.5$ velocity response



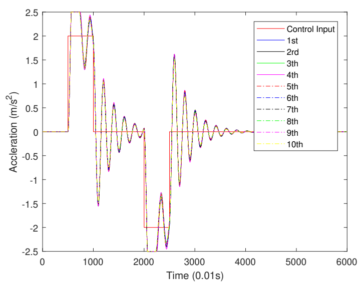
(f) $\tau_i = 0.5$ acceleration response



(g) $\tau_i = 0.6$ spacing error response



(h) $\tau_i = 0.6$ velocity response

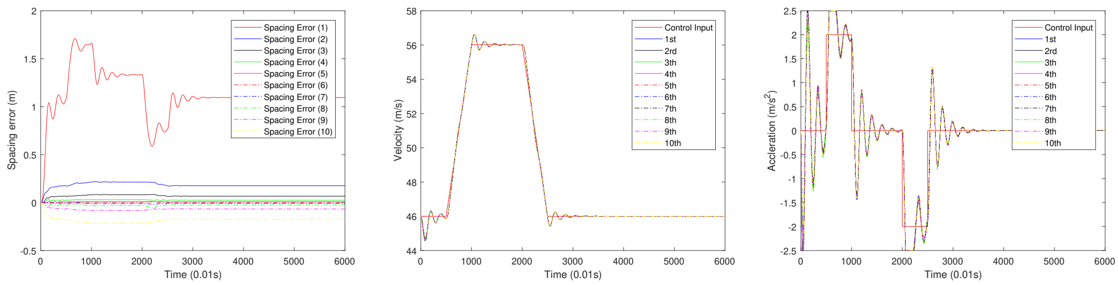


(i) $\tau_i = 0.6$ acceleration response

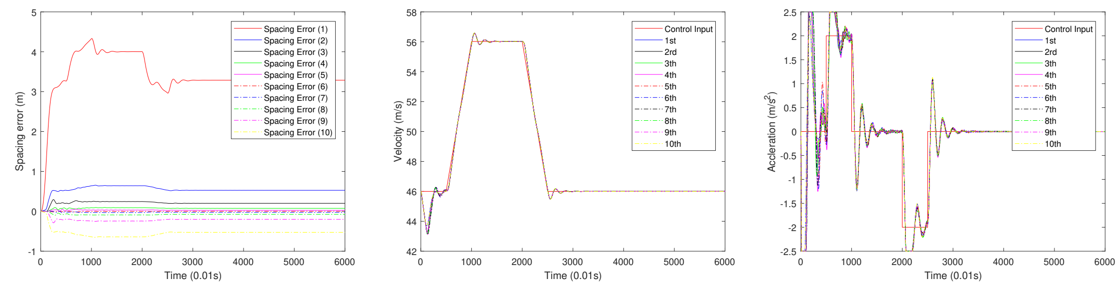
Fig. 5.9 τ_i with the platoon system response

Communication delay

In this simulation, it changes the τ_i for a single vehicle, for which the acceleration is $\tau_i = 0.5$ and the deceleration is $\tau_i = 0.6$ with 0.01 variance Gaussian white noise. Then, it adds the communication delay t = 0.02s and t = 0.04s to test the performance of the controller. Fig.5.10 shows the space error results, velocity results and acceleration results with respect to the 0.02s and 0.04s communication time delay. In the figure, from 0.02s to 0.04s communication, it can be seen only 0.02s is added to the communication delay. Due to this, the overshoot and oscillation of the system will be greatly increased. The system can become unstable and difficult to control. Therefore, communication delay will be a prerequisite for vehicle platoon and vehicular driver-less technology.



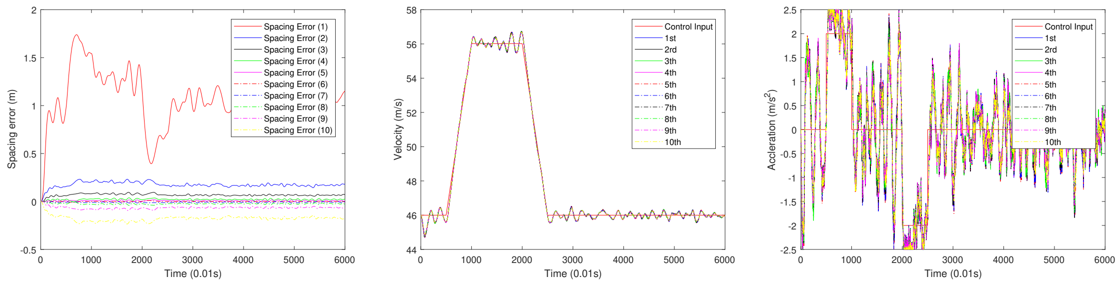
(a) Space error response with 0.02s communication delay (b) Velocity response with 0.02s communication delay (c) Acceleration response with 0.02s communication delay



(d) Space error response with 0.04s communication delay (e) Velocity response with 0.04s communication delay (f) Acceleration response with 0.04s communication delay

Fig. 5.10 Communication delay with platoon system

In order to make the simulation realistic, the communication delay was changed to a random variable between 0.01s to 0.03s and the result obtained is shown in Fig.5.11. According to the results, the controller has been trying to adjust the controlled object to the set parameters. However, it can be seen that the inter-vehicle spacing of the entire vehicle platoon is convergent. The acceleration changes are relatively large, so the hardware requirements for the acceleration of the vehicle will be very high. Therefore, the vehicle equipment in the vehicle platoon control, such as sensors, radar and power output equipment, is very demanding due to a floating communication delay.



(a) Space error with communication delay (b) Velocity with communication delay (c) Acceleration with communication delay

Fig. 5.11 Random dynamic communication delay

5.7 Summary

This chapter proposes an SMC controller with a virtual lead vehicle information and V2V and V2I communication (global communication) to control EVs driving along a TEV lane. The investigation highlighted the influence of the controller parameters and the communication delay. TEV with this controller is considered as a possible solution for HTS. The main idea of TEV is that EVs drive within a dedicated lane at 200km/h with an inter-vehicle distance of 0.25 car lengths. The short distance is the biggest challenge for every platoon controller to achieve accuracy and stability. The proposed controller is able to achieve these targets by introducing a new and simple method for determining the first order vehicle linear system identification and by guaranteeing that the designed controller shows non-homogeneous string stability in a platoon. Future research may include the effectiveness of the real vehicular platoon scenarios with the proposed SMC controller and use 5G (5th generation mobile networks) for the V2V communication, making the entire system to be more user-centric.

The work in the next chapter moves to incorporate practical work. In real time, the position, speed and acceleration are challenges to measure. It needs multiply sensors collaboration. Furthermore, chapter 6 uses the GNSS to determine the position of each vehicle in a platoon system. The IMU is used for the acceleration detection in this case. The Kalman algorithm will be discussed for these data fusion in next chapter.

Chapter 6

Data Fusion Technology to Measure Vehicle Position

ITS aim to provide a safe, efficient and coordinated traffic system. V2V and V2I communication are both important components of the ITS. In this chapter, the protocol and model for the V2V communication OBU with assisted CACC will be developed for platooning scenarios. In the vehicular platooning system, vehicle position technology is always the primary concern for the entire platoon system and the vehicle itself. Although GNSS can provide position, navigation and timing (PNT) services, the accuracy is significantly degraded under dynamic environments. In order to obtain precise positioning information, this chapter describes IMU/GNSS data fusion to achieve a highly precise positioning solution. Such high precision of positioning is required where vehicles in a platoon arrangement drive at very high speed. If the control rule is based only on radar and internal sensors it cannot maintain a stable string compliant with CD policy. With the help of V2V communication, the dynamic information of the lead vehicle can be broadcast to any neighboring vehicle within the platoon system. Thus, SMC has been implemented in this chapter and the Lyapunov function is established to analyze the stability of the string. As a result, the performance of the SMC is compared and analyzed through both simulation and field experiment. In the simulation experiment, five vehicles are designed in the platoon system and these vehicles can obtain the information from both the leading vehicle and the preceding vehicle. The results show that the following vehicles can reach the same velocity and acceleration as the leading vehicle in 5 seconds and the spacing error is less than 0.1m. In the field experiment, it implemented cart test with a reference lead vehicle in the platooning system. The cart has IMU on board to collect the acceleration information and then the control rule is applied for post-processing. The practical results are in line with those from the simulated experiment.

The exact positioning technology of the vehicle is an unavoidable research problem, regardless of how the vehicle controller is developed. The controller has been discussed in detail in the earlier chapters of this thesis. A distributed controller for vehicle platoon is also designed in this chapter using SMC and V2V technology. The leader vehicle's positional information is obtained by combining IMU and GNSS data. As a result, the purpose of this chapter is to employ the cart to simulate the leading car in order to gather real position data in order to verify the vehicle platoon's performance.

6.1 Global Navigation Satellite System and Inertial Measurement Unit technology

GNSS is the generic term which provides PNT services with global coverage. It includes GPS (USA), Galileo (Europe), GLONASS (Russia) and Beidou (China) and various other regional navigation systems. Technically GNSS receivers can provide meter to sub-meter levels of accuracy. On stationary GNSS receivers, the accuracy can reach centimeter levels. However, the accuracy is capable of being significantly diluted in suburban environments due to dynamic and multipath effects. Thus, to obtain an optimal positioning solution, additional sensors are required. IMU or INS (Inertial Navigation Sensor) are commonly used for integrating navigation data [129]. Two types of GNSS/INS integration techniques widely used are loosely and tightly coupled integration techniques. Loosely coupled integration refers to the direct integration of the position and velocity information from the GNSS receiver and the INS measurement [120]. This is the most common integration method due to its easy implementation. On the other hand, integrating the pseudo range and pseudo range rate from the GNSS receiver and the INS measurement is called tightly coupled integration

[120]. This latter is more accurate and robust, however, it is commonly adopted for high grade INS, requiring highly accurate inertial measurement data. Therefore, this chapter presents a Kalman filter based GNSS/INS loosely coupled integration technique is implemented to yield a continuous and precise position solution. The aim of this chapter is to analyze the accuracy of the fusion data and understand how it used in the vehicular platoon system.

6.2 Kalman Filter for Data Fusion

6.2.1 Kalman Filter Algorithm

This chapter briefly introduces the Kalman filter algorithm as demonstrated in [130][131]. Consider the normal Kalman filter model as:

$$x_t = F_t x_{t-1} + B_t u_t + w_t, x_t = \begin{bmatrix} p \\ \\ v \end{bmatrix} \tag{6.1}$$

$$z_t = H_t x_t + b_t \tag{6.2}$$

where x_t is the state vector at time t, p is the position and v is the velocity at the time t, u_t is the control input vector. F_t is the state transition matrix. B_t is the control input matrix, w_t is the process noise in the state vector and the covariance matrix is Q_t, z_t is the measurement vector. H_t is the transformation matrix that connect the state vector and the measurement vector, b_t is the measurement noise of on-board sensors and the covariance matrix R_t. Both v_t and w_t are assumed as zero mean Gaussian white noise. In this context it uses the basic Kalman filter for data fusion. The Kalman filter algorithm has two steps: Prediction and Measurement update.

$$\widehat{x}_{t|t-1} = F_t \widehat{x}_{t-1|t-1} + B_t u_t \tag{6.3}$$

$$P_{t|t-1} = F_t P_{t-1|t-1} F_t^T + Q_t \tag{6.4}$$

Equation 6.3 and 6.4 are the prediction equations, $\widehat{x}_{t|t-1}$ is the prediction value of the state x_t, $P_{t|t-1}$ is the covariance of $\widehat{x}_{t|t-1}$ where $P_{t|t-1} = E[(x_t - \widehat{x}_{t|t-1})(x_t - \widehat{x}_{t|t-1})]$. Then the updated equations are:

$$\widehat{x}_{t|t} = \widehat{x}_{t|t-1} + K_t(z_t - H_t\widehat{x}_{t|t-1}) \tag{6.5}$$

$$P_{t|t} = P_{t|t-1} - K_tH_tP_{t|t-1} \tag{6.6}$$

$$K_t = P_{t|t-1}H_t^T(H_tP_{t|t-1}H_t^T + R_t)^{-1} \tag{6.7}$$

K_t is the Kalman gain for each update. Using these updated equations, it can regress itself within the loop. Now consider the longitudinal control of platoons, its dynamic can be regarded as one-dimensional behavior. Thus, this model can be established as:

$$x_t = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} x_{t-1} + \begin{bmatrix} \frac{1}{2}\Delta t^2 \\ \Delta t \end{bmatrix} a_{t-1} + \begin{bmatrix} 0 \\ t \end{bmatrix} \sigma \tag{6.8}$$

Where, Δt is the sample time, σ is the zero mean Gaussian noise. Additionally, in the measurement vector, it plans to obtain the position information from GNSS receiver and the velocity information from the IMU by integrating accelerator's data.

6.2.2 Optimal Weighted Fusion

In this section, the optimal weighted fusion algorithm is used for multiple sensors. It is widely used for the data fusion. It assumes that N sensors are used to measure one objective i.e. vehicle. As in equation 6.2, b_t is the measurement noise of on-board sensors and is equal to $[b_1b_2...b_n]_t$,n is the number of sensors. It accepts that $b_i \sim N(0, \sigma_i^2)$ and b_i, b_j independent when $i \neq j$. Hence, σ_i^2 is the noise of sensor i [132].

Consider N sensors measured value with the weighted is equal to the actual estimated value, which is:

$$\widehat{x}_t = \sum_{i=1}^{n} \omega_i x_{it} \tag{6.9}$$

ω_i is the value of the weight for the sensor i and for keep unbiased estimation that $\sum_{i=1}^{n} \omega_i = 1$. This is the condition of the optimal weighted fusion algorithm. Because all sensors are independent, so that it can build the error of the weighted estimation function as:

$$\delta = E[(\widehat{x_t} - x_t)^2] = \sum_{i=1}^{n} \omega_i^2 \sigma_i^2 \tag{6.10}$$

δ is the expectation of the estimated error. From these equations, one can know that the solution is a multivariate function with extreme problem solving under constraints. Mathematically the solution is:

$$\omega_i^* = \frac{1}{\sigma_i^2 \sum_{j=1}^{n} \frac{1}{\sigma_j^2}} \tag{6.11}$$

ω_i^* is the optimal rate of this fusion algorithm.

6.3 Fusion Data in Classical Controlled Platoon System

In this section, the SMC controller has been designed into two types, which are reference lead vehicle and actual lead vehicle. In SMC with V2V communication platoon system, the lead vehicle can broadcast dynamic information within the platoon. With the reference lead vehicle, as described last chapter which shown in Fig 5.4(Fig 6.2 in this chapter). The master controller can broadcast information for every platooning system, which pass this highway. Thus, the dynamic information requirement depends on the traffic flow, weather and construction situations. The overall slide surface with the information flow as shown in Fig.6.1 can be described as [82]:

$$S_i = \dot{e}_i + q_1 e_i + q_3(v_i - v_l) + q_4(x_i - x_l + \sum_{j=1}^{i} L_j) \tag{6.12}$$

This simply magnifies the velocity and spacing error between lead vehicle and vehicle i. The parameters q_1, q_3 and q_4 are the gains. Equation 6.12 does not have any gain for $\dot{e}_i$ as the calculated input of the controller that gain is cancelled. The control input can then be

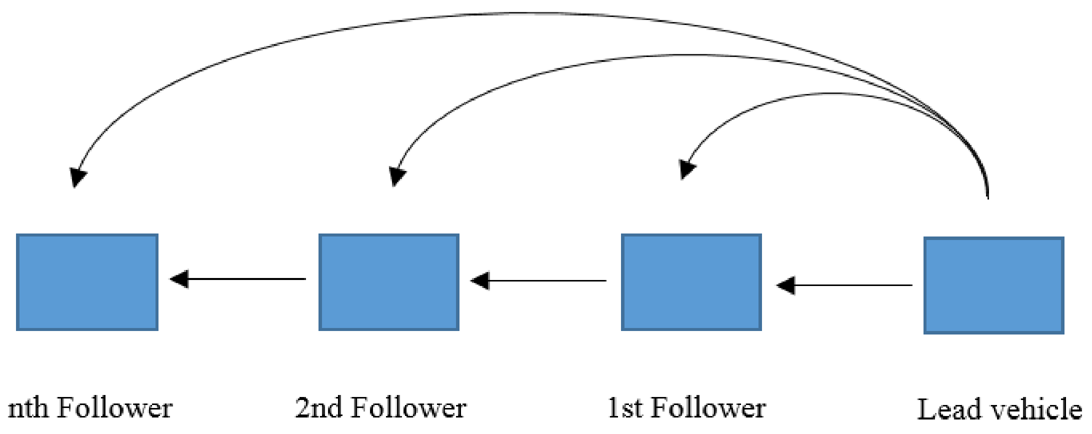


Fig. 6.1 Vehicular platoon information flow

designed as:

$$\dot{S}_i = \lambda S_i \tag{6.13}$$

Where λ is a positive constant. Now it considers that the slide surface is reachable in a certain time t_r [107]. Take the Lyapunov function that

$$V_i = \frac{1}{2} S^i_2 \tag{6.14}$$

Then:

$$\dot{V}_i = S_i \dot{S} i = -\lambda S_i^2 \tag{6.15}$$

In this case, when $S_i \neq 0$, $\dot{V} \leq 0$. So as the time t goes to infinity, the slide surface becomes asymptotically stable. Moreover, for a typical platoon it must consider the string stability. When the spacing error dynamics on the surface S_i and guarantee the string stability so that it has $S_i = S_(i-1) = 0$. Then it has the error transfer function which is:

$$H_i(s) = \frac{e_i(s)}{e_{i-1}(s)} = \frac{q_1}{q_1 + q_4} \tag{6.16}$$

q_1 and q_4 both are positive so the magnitude of $H_i(s)$ is always less than 1 when i=1,2,3,...,n. So, proving the spacing error cannot be increasing towards the platoon system.

In addition, with this slide surface it can obtain the controller input which is:

$$u_i = \frac{1}{1+q_3}[a_(i-1) + q_3 a_0 - (q_1+\lambda)\dot{\varepsilon}_i - q_1\lambda\varepsilon_i - (q_4+\lambda q_3)(v_i - v_0) \\ -\lambda q_4(x_i - x_0 + \sum_{j=1}^{i} L_j)] \tag{6.17}$$

It has been pointed out in [26] that the difference value of the input transfer function is the same with the spacing error transfer function, which is:

$$u_i - u_{i-1} = H_i(s)(u_{i-1} - u_{i-2}) \tag{6.18}$$

Consider the equation when the actuator and signal communication lag the control input, it has the relationship with the actual acceleration as shown in equation 6.12. Then the lags τ cancel so that:

$$\frac{\tau s a_i + a_i - \tau s a_{i-1} - a_{i-1}}{\tau s a_{i-1} + a_{i-1} - \tau s a_{i-2} - a_{i-2}} = H_i(s) \tag{6.19}$$

Now it can be shown that the transfer function is the same as the spacing error transfer function thus the result of string stability polynomial of the platoon system with lags is still $H_i(s) = \frac{q_1}{(q_1+q_4)}$ and less than 1 [133], or it is within the unit cycle, so it is stable.

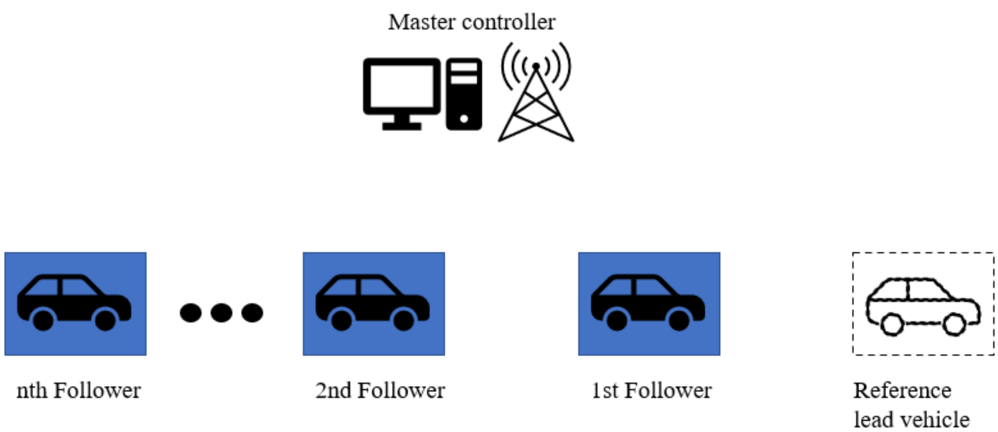


Fig. 6.2 Vehicular platoon system with reference vehicle

Now consider the platoon system as in Fig 6.2. It assumes that it has a master controller to broadcast the dynamic information e.g. velocity and position for the platoon system. Thus, this control strategy is similar to the Mini-Platoon Control Strategy [26]. However, in the Mini-Platoon control strategy the platoon is divided into smaller platoon systems. That is why it is called the Mini-platoon control. In this chapter, it is proposed a reference lead vehicle with the segments of highway, meaning in this segment, it only has one platoon system. Then, the modified equation 6.15 is:

$$S_i = \dot{e}_i + q_1 e_i + q_3(v_i - v_{ref}) + q_4(x_i - x_{ref} + \sum_{j=1}^{i} L_j) \tag{6.20}$$

which, v_{ref} and x_{ref} are the velocity and position of the reference lead vehicle respectively. To analyze the stability of this platoon system, there is no difference with the structure of Fig 6.1. and it can use the same method to study it.

6.4 Numerical Simulation Results

In this numerical simulation, the number of vehicles is constant - five vehicles with one lead vehicle and four followers. There are no initial spacing errors in the platooning and there is no initial velocity error as in Table 1. The acceleration and deceleration motion of the vehicle is regarded as a disturbance. The trajectory of the pilot vehicle is set to:

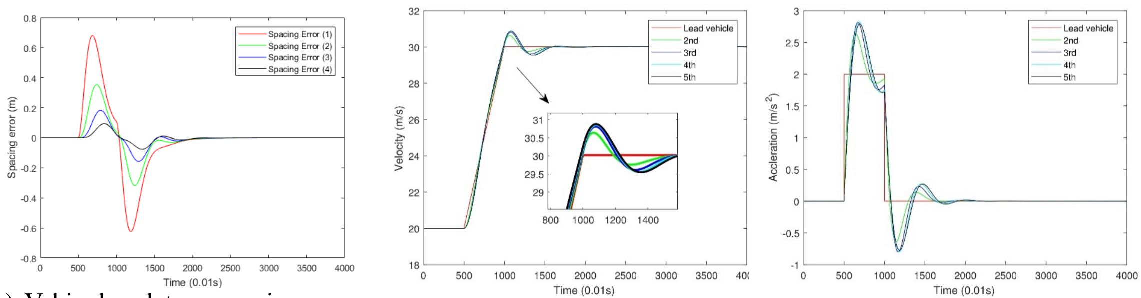
$$v_0 = \begin{cases} 20; 0 < t \le 5 \\ 2t; 5 < t \le 10 \\ 30; t > 10 \end{cases} \tag{6.21}$$

Then, the vehicles in the platoon system are initialized as in the table below:

Table 6.1 Initial State Set of the Platoon System

	Lead Vehicle	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5
Position	50m	40m	30m	20m	10m
Velocity	20m/s	20m/s	20m/s	20m/s	20m/s
Acceleration	$0m/s^2$	$0m/s^2$	$0m/s^2$	$0m/s^2$	$0m/s^2$

Now the control parameters can be set as q_1=1, q_3=2 and q_4=1, λ=0.7 and τ=0.5 . The results are shown in Fig 6.3.

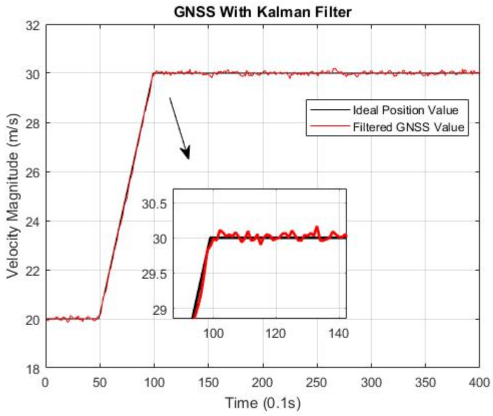


(a) Vehicular platoon spacing error (b) Vehicular platoon velocity (c) Vehicular platoon accelerations

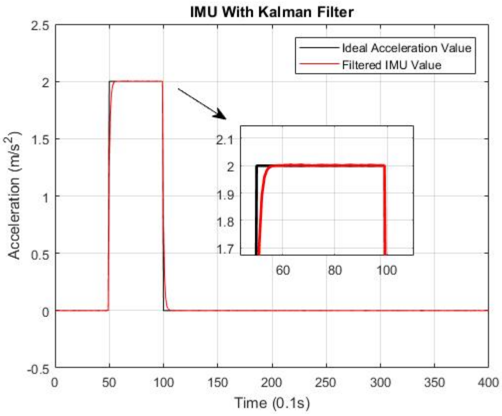
Fig. 6.3 Platoon system response

Fig 6.3(a) shows the spacing error response with respect to time, the error converges towards the platooning system. So, this result validates that the system, using this controller, is string stable. Fig 6.3(b) is the velocity response, the zoomed figure clearly shows that all the velocities of the vehicles have matched the same velocity as the lead vehicle. In Fig 6.3(c), the red line is the ideal acceleration response. All the vehicle accelerations' coverage is within 0-10s.

The next experiment uses the data technology with the slide mode control. Firstly, the vehicle behavior is designed as in Table 6.1. It adds gaussian white noise to the designed velocity and acceleration. The mean of the GNSS noise is 0.1 for the velocity, the mean of the IMU noise is 0.0012356 and the sample time is 0.1s. Two typical noises are chosen to simulate the GNSS receiver and accelerator in IMU. After which the Kalman Filter is used to address the generated velocity and acceleration data. Finally, the integral and derivative of filtered velocity and acceleration data is used to get the IMU velocity and GNSS acceleration data which is then combined with the IMU velocity and GNSS velocity to get the velocity fusion data. This is then combined with the IMU acceleration and GNSS acceleration data to get the acceleration fusion data. The results are as follows:



(a) GNSS velocity data with Kalman filter

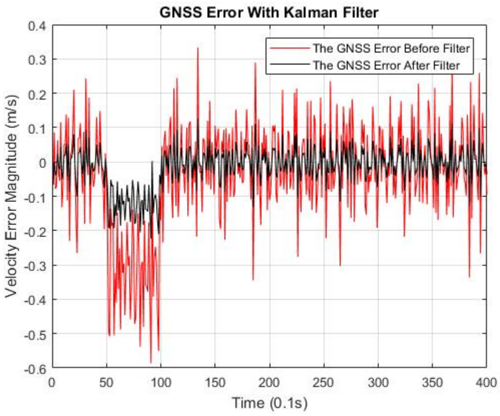


(b) IMU acceleration data with Kalman filter

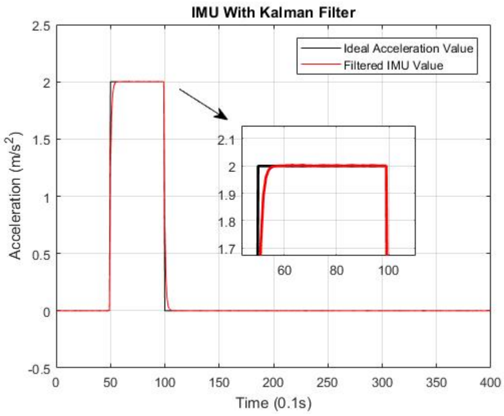
Fig. 6.4 Data after Kalman filter

After using the Kalman filter it can be observed that both the noise of GNSS velocity data and IMU acceleration data have slightly fluctuating values around the acutal value as in Fig 6.4(a) and Fig 6.4(b). Fig 6.5 the results shown compare the errors with the function of the Kalman filter for the GNSS and IMU. It can be seen that the errors have slightly decreased with this filter.

Fig. 6.6(a) is the result combined by the IMU acceleration and the derivative of the GNSS velocity. The noise of the acceleration fusion data is larger than the acceleration, which is only obtained from the IMU. In this case, the GNSS acceleration influences the accuracy of the IMU data. It is because the noise of the IMU is very small as in this study. Therefore, it is limited to one-dimensional vehicle dynamics. In addition, the GNSS noise value is larger than the IMU noise. After calculating the derivative of the GNSS velocity, the noise become even larger. In a real situation, the IMU can detect the acceleration from many directions, which can lead to errors. In Fig. 6.6(b), the result is combined by the integral of the IMU acceleration and the GNSS velocity. However, the IMU filtered value is closer to the real

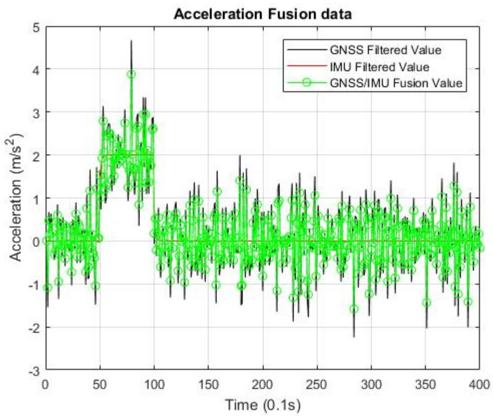


(a) GNSS error magnitude after Kalman filter

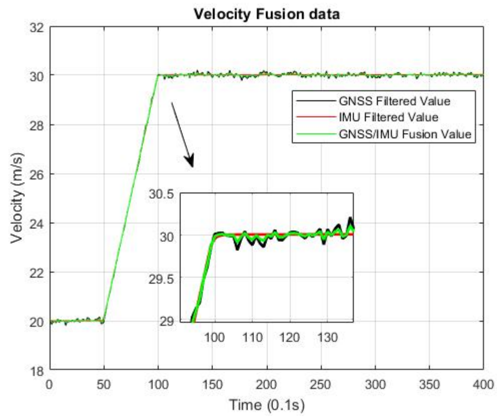


(b) IMU error magnitude after Kalman filter

Fig. 6.5 Error after Kalman filter



(a) Acceleration fusion data



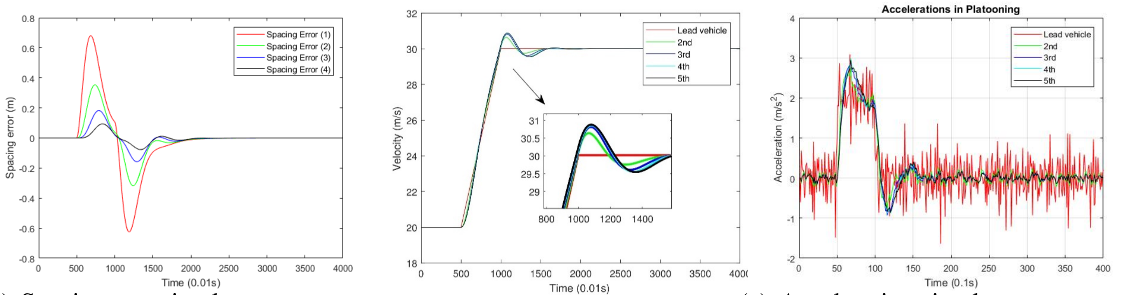
(b) Velocity fusion data

Fig. 6.6 Fusion Data

designed velocity. The GNSS value influences the result of the fusion value and makes it less accurate. It is because the noise of the IMU and GNSS are not of the same order of the experimental design. As a result, the IMU performance better that the fusion data in this experiment.

Then it uses the fused data to simulate the signals transfer from the lead vehicle to the following vehicles.

Fig.6.7 are the results of the spacing errors, velocities and accelerations of the following vehicles with the slide mode control. It is seen that the spacing error becomes convergent towards the platooning, which also proves that the system is string stable. In the velocity



(a) Spacing error in platoon system (b) Velocities in platoon system (c) Accelerations in platoon system

Fig. 6.7 Platoon system response

figure that the setting time is approximately 5s and this is acceptable for the following vehicles. In Fig.6.7(c) , the control has certain filtering function. The following vehicles accelerations didn't change too much by a floating lead vehicle acceleration.

6.5 Field experimental

To test the performance of the proposed approach, a field experiment was conducted in an open field, Newcastle University campus on 7th August of 2018. In the experimental study, the computer has collected data from the IMU. The IMU device is a Xsens IMU MTi-10 which is used to collect the acceleration measurements. Once it obtained the dynamic information of this cart it uses the USRP to simulate V2V communication with the designed SMC. Overall, in the physical simulation experiment, the devices assembled in the cart simulate the lead vehicle. The following vehicles are simulated with a slide mode controller and the parameters are the same as the numerical simulation. Firstly, the cart is pushed to get the acceleration measurement from the Xsens IMU MTi-10. Then with the USRP communication and the slide algorithm the following spacing error, velocity and acceleration can be obtained.

6.5.1 Experimental results with the Inertial Measurement Unit data

In Fig.6.9, the spacing error, velocity and acceleration are shown for the platoon system with the USRP for communication post-processing. The sample time is as the IMU sensor, which

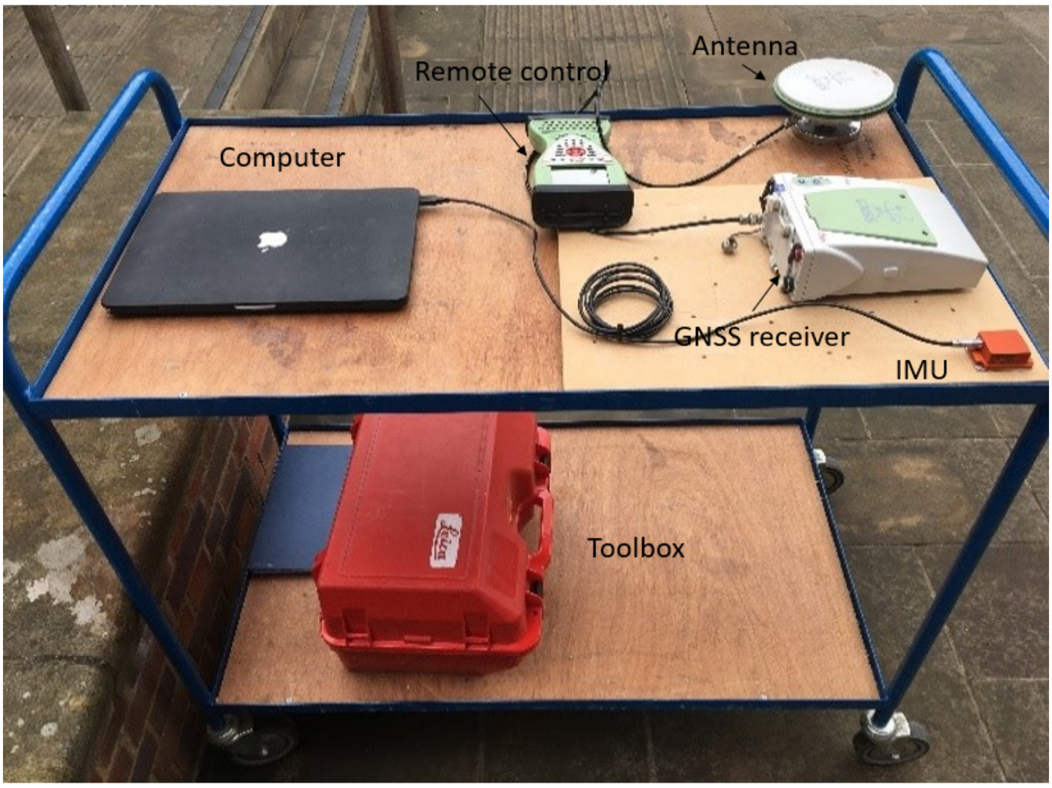
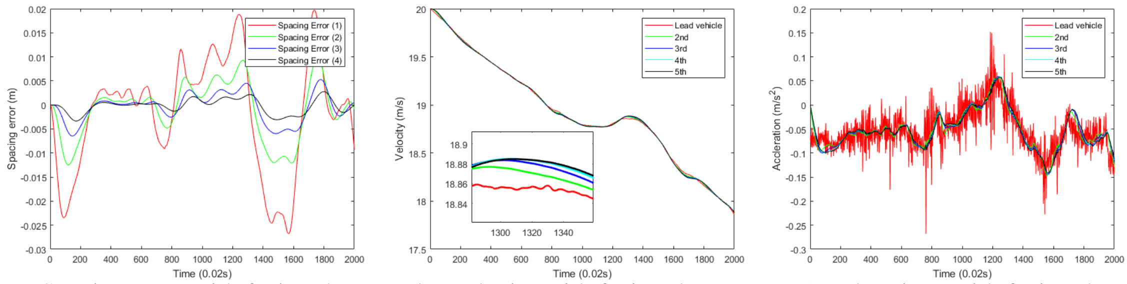


Fig. 6.8 Field cart experimental



(a) Spacing error with fusion data (b) Velocity with fusion data (c) Accelerations with fusion data

Fig. 6.9 Platoon system response with fusion data

is 0.02 sec. From the given 40 seconds data of the acceleration designed sliding mode control, the results are desirable. To simulate the real traffic situation, it sets the initial velocity as 20m/s. The initial spacing is given in Table 1. In the spacing errors as shown in Fig.6.9(a), there is an inverse relationship between the platooning size and the spacing error. As the platooning size increases, the spacing error decreases until it reaches point convergence. Moreover, it gets less towards the platooning system. Thus, it also validates that the system possesses string stability. Fig.6.9(b) shows that the velocity response has a marginal error. In addition, the velocity inputs for the platoons are smooth which is so sensitive by the floating velocity of the lead vehicle. The red curve in Fig.6.9(c) is the given acceleration of the lead vehicle. The following vehicles in the platoon have a lower error than the lead vehicle. As can be seen, the given acceleration oscillates significantly however due to the robustness of the slide controller the output is not influenced by this.

6.5.2 Data fusion results with Global Navigation Satellite system and Inertial Measurement Unit

Fig.6.10 presents the experimental trajectory, the comparison results indicate that the GNSS/IMU integrated result is more accurate than the GPS only results. GNSS positioning and speed measurement are highly accurate and are not limited by time or geography. But the signal will be affected by the terrain such as the tunnel and the building. In the red curve of 6.10, it can be clearly seen that the location performance has been diluted by the building

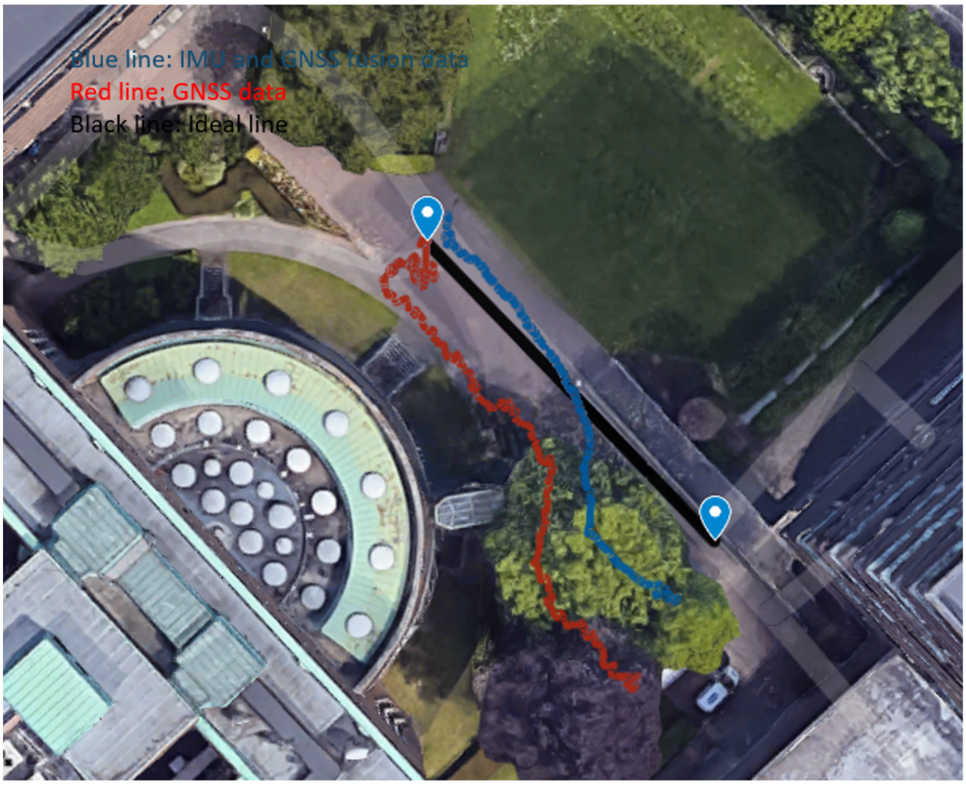


Fig. 6.10 The fusion data of the test lane

and trees. Now it needs the help of the IMU. IMU uses dead reckoning to obtain carrier information and the measurement accuracy is high in a short time. However, long-term work is likely to cause accumulation errors. As the result shows IMU/GNSS is a good way for navigation.

6.6 Summary

In this chapter, due to the rapid development of V2V communication, multiple vehicles control has become an important research area. Using the Lyapunov function method it can analyze the stability of the platoon system with the SMC control as it attempted. The simulation verifies that SMC control method can be used effectively in longitudinal valvular platooning this type of platooning is required for the TEV Project for example. Besides this, in the actual traffic system random phenomenon exists such as the V2V communication lost bag, weather and road conditions can all influence the platoon dynamic behavior. GNSS positioning and speed measurement are highly accurate but are not limited by time or geography [134]. However, the signal will be affected by the terrain such as tunnels and buildings, thereby requiring the use of IMU. IMU uses dead reckoning to obtain carrier information and the measurement accuracy is high in a short time. However, long-term work is likely to cause accumulation errors. As the result show IMU/GNSS is a good method for navigation. It is worth mentioning that GNSS and multiple sensor fusion methods are a potential way to determine the position, velocity and acceleration of vehicles. In the experiment in this chapter, the acceleration can be measured from the accelerometer and GNSS fusion. Hence, it possible to use the SMC method in real situations. However, it needs further experiments with actual vehicles to become completely reliable. Thus, the future work involves the study of platooning system by: (1) Use of multiple sensors fusion to get the dynamic information accuracy (2) Build more accurate model for vehicle dynamics (3) Design of the vehicle experiments considering real-time conditions.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

In this final chapter the project is summarised and conclusions about the main contributions and study on the vehicular platoon system. This study is part of the TEV project, which aims to be the safest, fastest and most versatile transport system possible with zero-emissions. The main idea of TEV is that EVs drive within a dedicated lane at 200km/h with an inter-vehicle distance of 0.25 car lengths. The short distance is the biggest challenge for every platoon controller to achieve accuracy and stability. So the controller design method, hardware of the vehicles and the communications are the key to this problem. Due to this, this thesis focus on the distributed controller design method, the communication delay and the sensors techniques are summarised as follows.

Firstly, a novel fuzzy-PID controller with V2V communication was designed for a car-following system and vehicular platoon system. The closed-loop stability and string stability was verified using the Routh-Hurwitz and polynomial methods. With the stability margin, the designer can easily choose the parameter values in the controller. The experimental results prove that this method met the modern control requirements of the vehicle platoon systems and the distance between the vehicles gradually attenuated in the direction of the platooning, indicating that string stability was maintained. It studied the influence of communication delay on the designed controller. This controller maintained superior characteristics than traditional a PID controller. Especially in the negative inter-vehicle spacing error, performance exceeded the PID controller. In the study of node vehicle parameter τ with the proposed controller, a larger τ value caused difficulty in vehicle control. If the delay changed considerably, the system lost stability. Therefore, the string stability and communication stability of the designed controller are two vital conditions for achieving an effective vehicle platoon. Secondly, this thesis proposes an SMC controller with a virtual lead vehicle information and V2V and V2I communication (global communication) to control EVs driving along a TEV lane. In here, this work successfully studied the influence of the controller parameters and the communication delay. TEV with this controller is considered as a possible solution for HTS. With the verified the simulation results, the proposed controller is able to achieve these targets by introducing a new and simple method for determining the first order vehicle linear system identification and by guaranteeing that the designed controller shows non-homogeneous string stability in a platoon. After verifying different parameters and communication delays, it can be concluded that the proposed controller under poor communication quality with BDL topology structure and can also guarantee a small inter-vehicle space, which is able to meet design requirements.

Thirdly, due to the rapid development of V2V communication, multiple vehicles control has become an important research area. Using the Lyapunov function method it can analyze the stability of the platoon system with the SMC control as it attempted. The simulation verifies that SMC control method can be used effectively in longitudinal vehicle platooning this type of platooning is required for the TEV Project for example. Besides this, in the actual traffic system random phenomenon exists such as the V2V communication lost bag, weather and road conditions can all influence the platoon dynamic behavior. GNSS positioning and speed measurement are highly accurate but are not limited by time or geography [134]. However, the signal will be affected by the terrain such as tunnels and buildings, thereby requiring the use of IMU. IMU uses dead reckoning to obtain carrier information and the measurement accuracy is high in a short time. Additionally, long-term work is likely to cause accumulation errors. As the result show IMU/GNSS is a good method for navigation. It is worth mentioning that GNSS and multiple sensor fusion methods are a potential way to determine the position, velocity and acceleration of vehicles.

Finally, this work demonstrated the real vehicular platoon scenario with the remote control toy vehicles. The Raspberry Pi is used for the control board and communicate to the computer. The supersonic sensor is used to measure the distance between vehicles. It also uses the PWM technology to control the motor. To control the feedback speed of the vehicles, the Hall sensor and the magnet has been installed on the wheel. It designed a two cars platoon system (car-following system) use the basic linear controller. The results shows the sensors and motor worked effectively with the linear controller.

7.2 Future Work

In the future, the work of this thesis can also be expanded into two parts: control algorithm and the hardware. With the development of communication technology, each vehicle can obtain more dynamic data of other vehicles in the vehicle platooning. These data can be used as a reference to assist the vehicle in driving. Therefore, in the study of control algorithms, more inputs such as road conditions and traffic density can be added in the future. The controller can also introduce AI technology to analyze these data. In the hardware, image processing technology can be used to determine the distance of the vehicle in front, and this distance data can be fused with sensors, GPS, etc. to further improve the accuracy of vehicle positioning. In the design of the simulation car, the work plans to improve our RC vehicle in more complex scenarios that include: (a) adding IMU sensor and GPS model to measure the acceleration and position (b) design a V2V communication to obtain the speed from the lead car. This setup will contribute to future contact-less courier services, where importance will increase during emergency situations such as COVID-19 pandemics in addition to the existing autonomous vehicle research. With the popularization of 5G technology, V2V communication will be developed based on this technology. Therefore, to summarize the future direction of this work is based on two points: 1) the algorithm is to improve the stability of the vehicle platoon system and reduce the inter-vehicle spacing. 2) The hardware design should be more in line with the real vehicle situation.

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Appendix A

Appendix: Practical Implementation of a vehicular platoon system

The appendix introduces a novel automated vehicle, based on Raspberry Pi and multi-sensors. The majority of automated cars utilise stop-and-go power systems, which motivated us to design a control variable speed car which is able to follow objects. It presents the design of the RC car, as well as the longitude control architecture. The experiments carried out implement state-of-the-art electrical vehicle structure with autonomous control strategies. It also tests the dynamic performance of the car and that of tracking objects. Our setup will contribute to future contact-less courier services, whose importance will increase during emergency situations such as COVID-19 pandemics in addition to the existing autonomous vehicle research.

A.1 The Overview of the remote vehicle

The deployment of network and autonomous vehicles changed people's inherent thinking about road transport [135]. Numerous companies and institutes are currently working to develop an ITS, such as Uber [136]. The car-following system is a sub-branch of the ITS study, which aims to increase the efficiency of road traffic [32]. An example where cars do not require lots of steering is described in the TEV Project where electric cars drive at

200 km/h on designated lanes in a platoon [137]. Car-following describes the interactions between a car and its preceding vehicles or objects within the same lane [138]. However, in the existing robot car research, they only use the stop and go function of a motor, which lacks the control of the speed of the motor for obstacle avoidance [139], vehicle image processing [140], etc. Due to this, there is a significant gap in the development of automated vehicles which can reliably deal with everyday traffic situations.

This research used the Raspberry Pi for the software control. The Raspberry Pi was developed by the Raspberry Pi Foundation, a charity registered in the United Kingdom in 2012 [141]. As an open source platform, the Raspberry Pi is both open for software and hardware and has rich hardware interfaces such as Inter-Integrated Circuit (I2C) and General-Purpose Input/Output (GPIO), which is suitable for electronic design. Raspberry Pi is an obvious choice to study V2I communication for researchers owing to its wireless communication and low design cost [142].

This work proposed the design of a RC vehicle, which is based on the model of a commercial toy car. The designed vehicle is low cost, multi-functional and possesses a small volume with real electrical vehicle structure. Overall, the main novel outputs of this work are (1) the design of RC vehicle based on Raspberry Pi and multi-sensors, (2) a method to control the speed of the car following the distance of an object, (3) vehicle design code compilation in python for public access.

A.2 Remote vehicle design

A.2.1 Power Supply Configuration

The RC vehicle is designed with a Raspberry Pi 4B as the control unit, a chassis with 4 wheels, a forward drive motor and steer servomotor and a 9.6 V lithium battery. Fig.1 shows the overall configuration diagram of the car. The size is 30 cm$\times$16 cm$\times$10 cm and it weighs 700 g (including battery). A battery of 9.6V is supplied directly to the motor. This battery can decrease to 5 V for the Raspberry Pi,sensors, A/D converter, steer servomotor by 5 V, 3.2 A Step-down voltage regulator to meet their requirement. The servo logic and motor enable

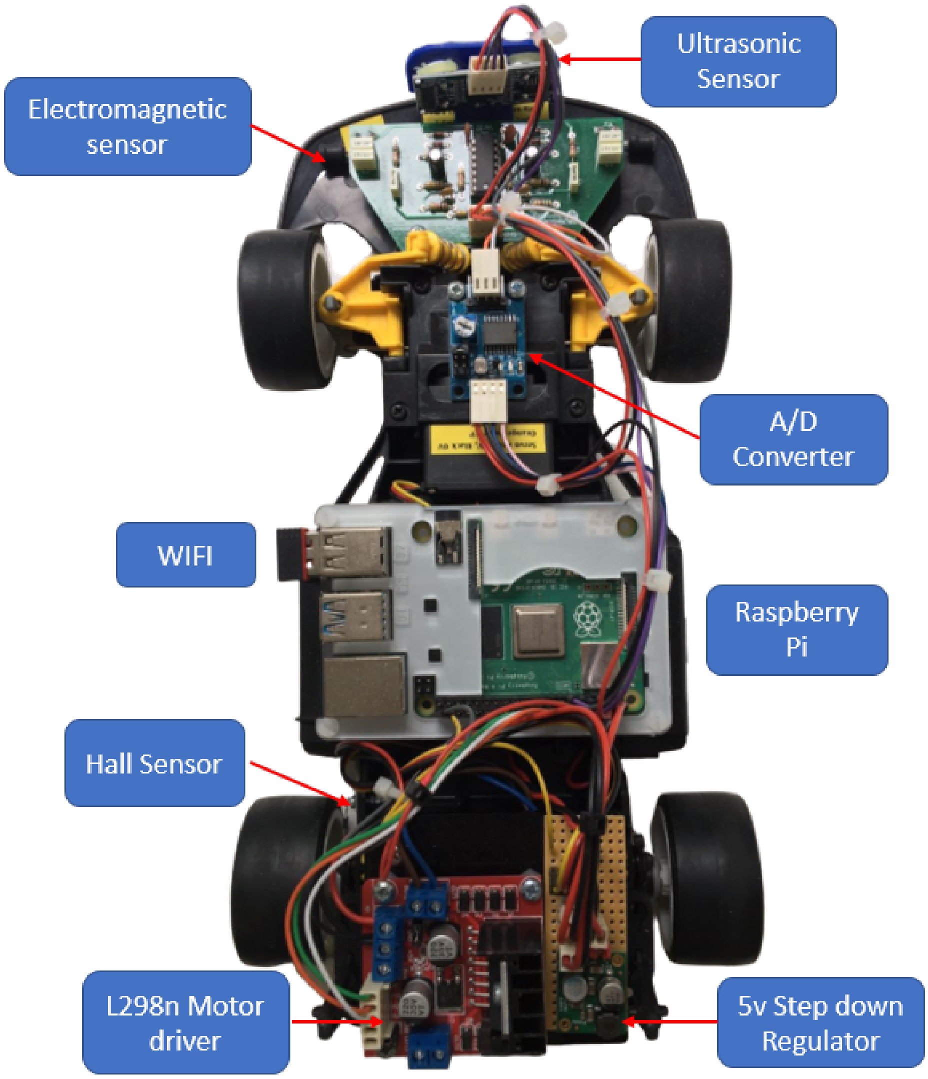

Fig. A.1 Remote Control Vehicle Assembly Diagram pin are controlled using PWM, by Raspberry Pi. All controlled components use Raspberry Pi GPIO port for data transmission.

The power consumption of Raspberry Pi 4B is reduced to 2.1 W at idle time and to 6.41 W at load. The ultrasonic sensor and the hall sensor consumptive less than 1 W. Therefore, the step-down regulator can supply 15 W, which is enough for the sensors and the raspberry pi. The L298n motor drive and the motor are powered by the 700 mAh battery. The advantage of this design set is that when the power supply is replaced, all components can work normally making the entire design flexible. The costs and the components of the vehicle lists in Table I.

A.2.2 Lateral Control

The main purpose of this work is not to control the steering of the car, so the details of the car steering will not be presented. However, in this work it has to keep the car go straight. So the general steer control method is also demonstrated in this work. In this system, the Raspberry Pi acts as the centre of the system. The left and right electromagnetic sensors have different voltages induced in them, depending on their distance to the centre of the track, as shown on the head of the vehicle of Fig.1. The track is a 5V, 10KHz AC loop wire from a signal generator. Then the analogue signal is picked up by the electromagnetic sensors and transferred to a digital signal from the A/D converter. The Raspberry Pi cannot accept analogue signal input, but the Raspberry Pi can receive digital signals from the I2C interface, which is a synchronous serial protocol used to transfer data between two devices. The Raspberry Pi obtains this difference input to a PID controller and then directs the steering of the servos and modifies the speed of the motors to ensure that the buggy remains in the centre of the track.

A.2.3 Longitudinal Control

Our longitudinal control diagram is shown in Fig.2. The ultrasonic and the speed sensor give the input signal to the raspberry pi. The raspberry pi uses this data to calculate the duty-cycle

Table A.1 Introduction of main components

Main components and prices			
Name	Model	Use	Price
Ultrasonic Sensor	HC-SR504	Used for measure the distance in front	£3.16
Raspberry Pi	Raspberry Pi 4 Model B 2GB	Center controller	£35.71
Motor Driver	L298n	Use PWM to control the motor	£4.99
WIFI Model	Ralink 5370	Wireless connect to PC	£7.99
Hall Sensor	A1120EUA-T	Measure the wheel speed	£0.71
Regulator	D36V28F5	Supply 5V,3.2A step-down voltage to power the vehicle	£11.47

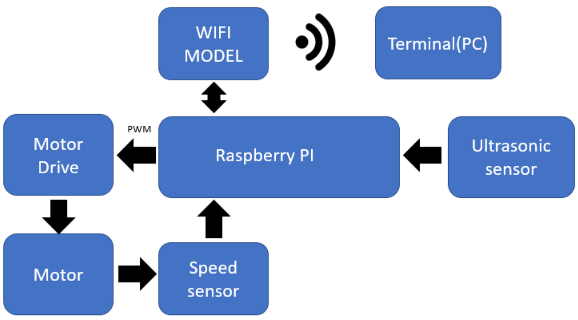

Fig. A.2 System block diagram

output to the motor drive. Following this, the motor starts to work or change its speed. This is the overall closed-loop structure of the longitudinal control and it is monitored by the PC, via Wireless Fidelity (Wi-Fi) network. In appendix, an empirical equation is used to derive a simple longitudinal control as follow;

$$D = k_1 \cdot d + k_2 \cdot \Delta v \tag{A.1}$$

where D is the duty cycle of the PWM signal to the motor drive, d is the distance form the preceding object, Δv is the velocity difference from the follow object if the follow can broadcast velocity and k_1 and k_2 are the setting parameters, depending on the actual physical environment of the car.

This work installed a small magnet on the edge of the wheel. The hall sensor will generate a voltage when the magnet passes the sensor, due to the Hall effect [143]. It will transfer the signal to the Raspberry Pi. The Raspberry Pi can calculate the speed of the vehicle using the time interval Δt (0.1 s) as follows;

$$\frac{2\pi r}{\Delta t} = v \tag{A.2}$$

where v is the car speed and r is wheel radius.

The Wi-Fi module allows the car data to be instantly uploaded to the computer for display by connecting to the same Wi-Fi network. The computer can also control the starting and stopping of the car, as well as the wheel speed at any time. It should be noted that it assumed a linear relationship between the speed of the car and the PWM duty-cycle of the control output.

A.2.4 Control Algorithm

The control program of this car is compiled in Python.The communication method used is 4G cellular network, where the Raspberry Pi and the PC must be connected to the same 4G network. As algorithm 1 shows, the Raspberry Pi enables the GPIO, the I2C channel and each sensor i.e. speed sensor, ultrasonic sensor etc. With the values from the sensors, the Raspberry Pi will calculate the output to the motor which is the PWM duty-cycle. The program will then repeat this process until the user exits the program.

Algorithm 1 Car-following Algorithm for Raspberry Pi

1: Set the vehicle speed sensor and the ultrasonic sensor, the distance d, the speed v, the frequency of PWM wave.
2: **while** True **do**
3: The sensors collects all the state infromation from vehicle.
4: Raspberry Pi uses distance d to calculate the dutycycle D of the PWM.
5: Send D the motor drive board.
6: Obtain the speed v from the wheel speed sensor and record.
7: **end while** user interrupts the program.

Fig. A.3 Control Algorithm

A.3 Car Performance Test

The dynamic performance of the car was tested at the Sports Center, Newcastle University. It used the mobile phone 4G cellular network to provide a hot-spot for the PC and RC vehicle to connect. The first experiment was the speed performance when the vehicle has no load. The speed results are shown in Fig.3. The sampling time is the time for the wheel to make one revolution and was set to 0.1 s. It ignored the static friction in the mechanical process during the first 1 s, shown in Fig.3. This then allowed us to calculate the mean speed with different PWM duty-cycle outputs. It obtained the experimental results so that the speed is constant under different PWM duty-cycle.

Under the same conditions, it placed the experimental car on the ground to test the dynamic performance of the car. The results are shown in Fig.4. The figure shows the car has speed noise due to the static friction in the first 10 s, which is not expected as it has complex mechanical dynamics. Spaces from 10 s to the end, the speed is relatively constant with 50%, 60% and 70% PWM duty-cycle. When the duty-cycle is under 50%, the car remains stationary.

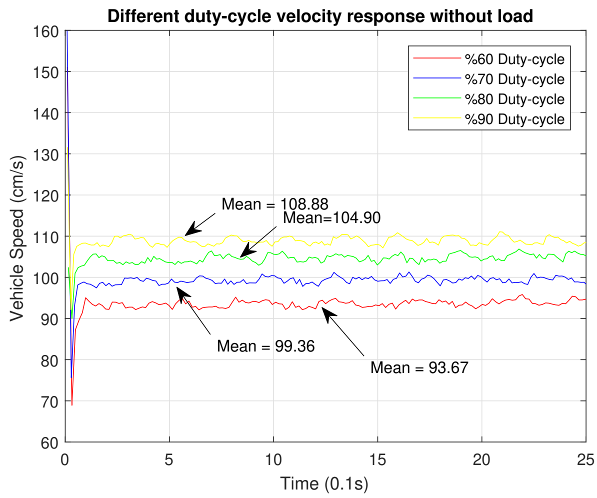

Fig. A.4 speed figure without load

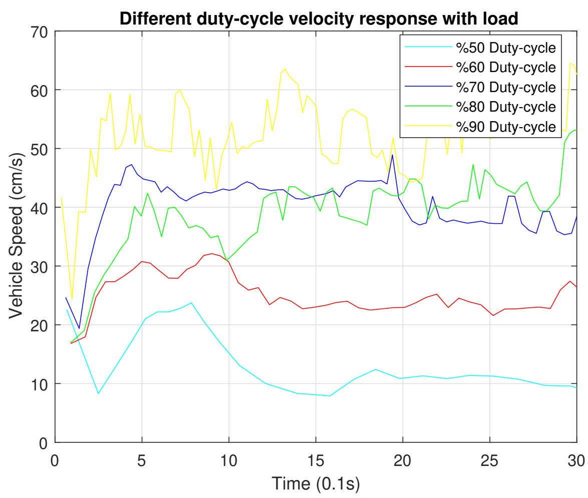

Fig. A.5 different duty cycle on ground

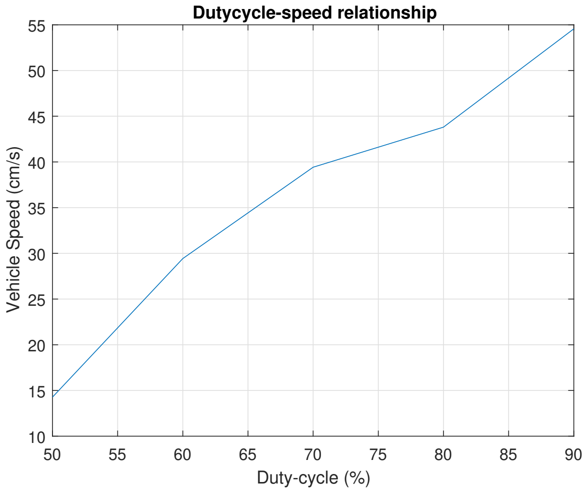

Fig. A.6 duty and speed

From the results, it then takes the mean of the speed after 10s which allowed us to develop the relationship between speed and duty-cycle, as shown in Fig.5 shows. In this figure, 50%, 60% and 70% PWM duty-cycle with the speed basically has a linear relationship. So in the next step of the algorithm, the output duty-cycle can be based on these results.

A.4 Car-following Experiment

In this car-following experiment, it uses this RC designed vehicle to follow a paper box as shown in Fig.6. In equation (1), it sets k_1=1 and k_2=0, since the box cannot broadcast the dynamic information. Generally, the vehicle measures the distance to the box first and changes it to the PWM duty-cycle output for the motor. Section 3 revealed that, the static friction is a big issue. Therefore, it removed the process of the car running against static friction. When the car is running, it placed a box between about 50 cm - 80 cm in front of the car and initiated the variable speed movement. The car can then track the AC loop wire with 5 V,10 KHz to guarantee it runs directly. It ran the experiments 5 times and superimposed the experimental results, shown in Fig.7.

This experimental tried to change the box within a small range, so the car will perform a variable speed movement at a variable range. However, when the distance is less than 50 cm,

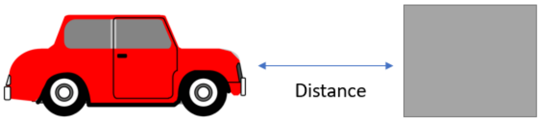

Fig. A.7 Experimental Setup

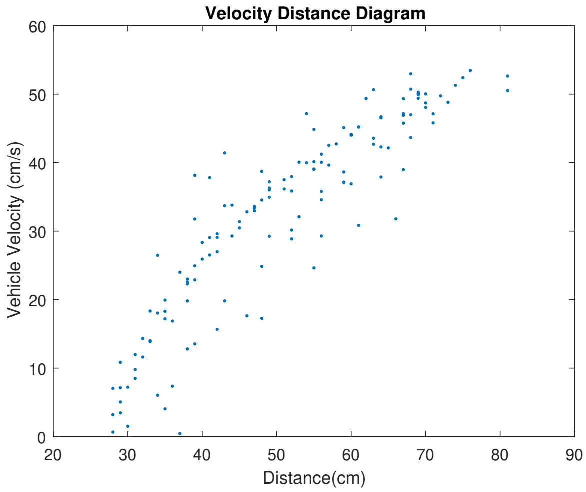

Fig. A.8 Experimental results

the car is stationary due to friction as shown in Fig.4. When restarted, the speed and distance relationship is nonlinear due to static friction. It can be seen from Fig.4 that the distance and speed are basically linear. When the distance is less than 40 cm, there is a rapid decrease in speed. This is because the car does not have a braking function, which means it brakes by friction. Consequently, the speed and distance relationship cannot remain linear.

A.5 Conclusion

Appendix A successfully shows the study used the Raspberry Pi to integrate various sensors, control steering and move forward. All sensor states are synchronized to the PC through the wireless network. It provided the design of RC car-following system for research, where the most favourable speed range is 30 cm/s – 50 cm/s. It presents the design of the control algorithm and the hardware procurement for other researchers to utilise. This experimental research demonstrates its applicability for a car-following system experimentation by following a box which leads to real traffic scenario. The platform also can also be easily extended with an IMU and GPS to provide acceleration and position.