Distributed Cooperative Autonomous Driving of Intelligent Vehicles Based on Spring-Damper Energy System

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***Abstract*— Distributed cooperative control of autonomous vehicle platoons has been widely considered as a potential solution for reducing traffic congestion, increasing road capacity and improving traffic safety. However, in the real-world implementation, sudden communication loss will degrade cooperative adaptive cruise control to adaptive cruise control, which may bring negative influences on safety (i.e., increase the risk of collisions). To overcome this limitation, this paper innovatively applies a spring-damper energy system to construct a robust leader-following vehicle platoon system. The special design of the energy system ensures that the stability and safety of the platoon system are maintained in the event of a sudden degradation. Based on the proposed energy model, a distributed control protocol is developed. The distributed control protocol achieves speed synchronisation of vehicle platoon and ensures that the following distance is safe over dynamic communication networks. Finally, the effectiveness of the proposed control strategy is validated by simulation experiments.**

I. Introduction

Cooperative Adaptive Cruise Control (CACC) enables longitudinal automation of connected vehicle platoons by utilising inter-vehicle distances primarily from on-board sensors and vehicle state information via vehicle-to-vehicle (V2V) communication [1]. This technique is able to shorten the inter-vehicle distance to alleviate traffic congestion, improve safety, fuel economy and traffic throughput while ensuring safety [2], [3].

In recent years, a large number of research works have conducted studies on multi-vehicle systems with remarkable success [4]–[7]. The traditional proportional integral derivative (PID) controller has been widely used as an effective control approach in Adaptive Cruise Control (ACC) and CACC. In the applications of PID control, the control input (such as acceleration/deceleration and target velocity) of an individual vehicle is obtained by a linear or nonlinear function using either the constant spacing strategy or the constant time headway strategy [8]. Model predictive control (MPC) is also widely used in CACC schemes. In addition to the following distance, those MPC methods also use energy consumption [9], comfort [10], and traffic efficiency [11] as an optimisation metric. In [12], the combination of distributed control and MPC also enables effective control of the vehicle platoon system. Other control methods are also being investigated, e.g., in [13], the stochastic optimal control strategy produced smoother vehicle control with small system disturbances and large measurement disturbances. In [14], a new control structure with optimal control and online learning was used to find the optimal error feedback, as well as to seek the minimum headway values. In addition, control methods based on a combination of data-driven and optimisation are gaining more and more attention from CACC researchers, where reinforcement learning has been shown in many studies [15], [16] to be a potentially practical approach to achieve autonomous vehicle platooning. However, these optimisation-based control algorithms and data-driven approaches place enormous demands on the computing power of the vehicle. At the same time, a truly data-driven approach to CACC control is limited to the laboratory and simulation platforms. Additionally, most of these CACC algorithms above highly depend on the stability and accuracy of V2V communication. If V2V communication is attacked or lost (i.e., CACC degrades to ACC), the risk of vehicle collisions will increase.

Motivated by the aforementioned challenges in the area of CACC, in this paper, a Spring-Damper Energy System (SDES) is firstly utilised to construct the autonomous vehicle platoon. The stability and steady-state of the vehicle platoon system are analysed. A novel distributed cooperative control protocol is then designed to achieve the CACC function. The control protocol is shown to be effective and secure in both dynamic topology scenarios and V2V communication loss scenarios. To the best of authors' knowledge, such a SDES based strategy to implement a reliable autonomous vehicle platooning has not been found in the literature. Finally, the effectiveness of the proposed scheme for use in autonomous vehicle platooning scenario is validated.

II. Preliminaries and Problem Statements

A. Dynamic Model

For vehicle platoon control, the exact linearisation is applied to describe the upper-level longitudinal dynamics. Both the second-order differential models and third-order differential models are widely considered. Additionally, a local feedback linearisation control method is utilised to transform the nonlinear vehicle dynamics into a linearised model [17], [18]. The cooperative control of the vehicle platoon is mainly focused on the high-level manoeuvre design. Hence, to simplify the dynamics model, the air drag, rolling resistance, and actuator delay can be ignored in the vehicle dynamics

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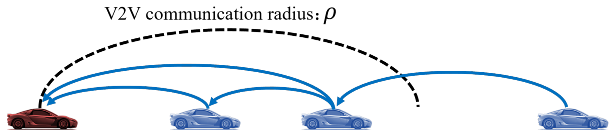


Fig. 1. V2V communication connections among the connected vehicles.

model [12]. The upper-level longitudinal dynamics can be described using ordinary differential equations (ODE):

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = u_i(t), \end{cases} \tag{1}$$

where $x_i(t)$, $v_i(t)$ and $u_i(t)$ are the position, velocity and control input of vehicle i, respectively.

B. Communication Topology

A time-varying directed graph $\mathcal{G}(t) \triangleq (\mathcal{V}, \mathcal{E}(t))$ is used to describe the network topology among the vehicles within the platoon, where $\mathcal{V} \triangleq \{\mathcal{V}_1, \ldots, \mathcal{V}_N\}$ is the set of nodes. The element of $\mathcal{E}(t) \in N \times N$ is denoted as $(\mathcal{V}_i, \mathcal{V}_j)$, which is termed an edge from $\mathcal{V}_i$ to $\mathcal{V}_j$. $A(t) = [a_{ij}] \in \mathbb{R}^{N\times N}$ is the adjacency matrix of graph $\mathcal{G}(t)$. $a_{ij} = 1$, if $\|x_i(t) - x_j(t)\| < \rho$, otherwise, $a_{ij} = 0$. $a_{ij} = 1$ means that the vehicles i can receive the information from vehicle j through V2V communication or on-board sensors. In this paper, we suppose that the initial connection topology of vehicle platoon is connected. The initial connection of the system is: $\mathcal{E}(0) = \{(i, j), | \, \|x_i(0) - x_j(0)\| < \rho, i, j \in \mathcal{V}\}$.

According to the [19], [20], we define a vehicle platoon network topology consisting of both on-board sensors and V2V communication. On-board sensors acquire information about the movement of the neighbouring vehicles, while V2V communication obtain the information about the movement of all vehicles within the communication range. The connection topology of the vehicle platoon is unidirectional. Fig. 1 describes the V2V communication connection relationship between vehicles, where the communication radius of the red car is ρ. It can be seen that the red car does not establish a communication link with the blue one that is outside its communication radius. Additionally, to eliminate the risk of collision due to complete loss of V2V communication, vehicles add on-board sensors to obtain status information of the nearest neighbouring vehicle.

C. Variable Definition of Vehicle Platoon

Consider a homogeneous platoon with N+1 vehicles with index from 0 to N. The index 0 represents the leading vehicle and index 1 to N denote the following vehicles. l_i is the body length of vehicle i. x_i and v_i, respectively, are the position and velocity of the front bumper of vehicle i. $S_i := x_i - x_{i-1} - l_{i-1}$ is the distance between the front bumper of vehicle i and the back bumper of the vehicle $i-1$. Define a variable to denote the desired distance between vehicle i and vehicle j:

$$\hat{S}_{ij} = \sum_{k=j+1}^{i} d_k + \sum_{k=j}^{i-1} l_k \quad \forall i > j \geq 0, \tag{2}$$

where d_k represents the desired distance between the vehicle k and vehicle $k-1$.

D. Control Objectives

In this paper, we consider a vehicle platoon with leading vehicle having dynamic velocity v_o. The control algorithm proposed in this paper needs to achieve the following control objectives:

- To achieve the following steady state:

$$\begin{cases} \lim_{t\to\infty} \|x_i(t) - x_j(t)\| = \sum_{k=j+1}^{i} d_k + \sum_{k=j}^{i-1} l_k \\ \lim_{t\to\infty} \|v_i(t) - v_0(t)\| = 0 \end{cases}$$
$$\forall i > j \geq 0. \tag{3}$$

  This control objective implies that the following distance and speed of all vehicles within the platoon need to converge to the desired value.
- From the perspective of functional security, the temporarily loss of V2V communication may lead to platoon collision. Therefore, another important control objective is that when V2V communication is lost, the connection topology of the platoon does not completely disconnect and the vehicle platoon continues to converge to the desired steady state.

III. Distributed Cooperative Control Design

In this section, we design a distributed cooperative control protocol for the vehicle platoon system by introducing a SDES. This control protocol is capable of achieving all our predefined control objectives.

A. Spring-Damper Energy System

In this paper, we consider a platoon system from a very novel perspective, i.e., system energy. We start by constructing a basic SDES as shown in Fig. 2, where the subsystem consisting of A_1, A_2, K_{12}, and c_{12}. Define A, c, and K as the agents, damping elements, and spring elements, respectively. In addition, we define energy in the energy model as follows:

$$\begin{aligned} E_A(t) &= \frac{1}{2}v(t)^2 \\ E_K(t) &= g(\Delta l_A(t)) \\ E(t) &= E_A(t) + E_K(t), \end{aligned} \tag{4}$$

where $E_A(t)$, $E_K(t)$, and $E(t)$ are, respectively, kinetic energy of agents, potential energy stored in the spring, and total current energy of the system. $\Delta l_A(t)$ denotes the distance between agents, and g is a function of $\Delta l_A(t)$.

For the energy system defined above, assume that the system has a finite initial energy, the system will achieve asymptotic stable in the absence of external energy input.

The time-varying energy function of the system is as follows:

$$E(t) = \frac{1}{2}v_1(t)^2 + \frac{1}{2}v_2(t)^2 + g(\Delta l_A). \tag{5}$$

In this spring-damper system, the damping unit and the spring unit together provide acceleration to the agents, which satisfies the following equation

$$a = -\nabla g - c\Delta v, \tag{6}$$

where $c > 0$ is the damping coefficient. The derivative of this function with respect to time gives:

$$\begin{aligned}\dot{E}(t) &= v_1(-\nabla g - c\Delta v) + v_2(+\nabla g + c\Delta v) + \Delta v \nabla g \\ &= -c\Delta^2 v \leq 0,\end{aligned} \tag{7}$$

which means the system energy is progressively stable. The derivative of (5) with respect to time shows that the spring-damper energy system will converge to a steady state where $\Delta v(t)$ equals 0, and $\Delta l_A(t)$ equals constant.

Based on the above definition, we take such a basic spring-damping energy system unit and form it into a more complex energy system by connecting it in series and parallel. We consider using a particular spring-damping energy model (shown as Fig. 2) to simulate a vehicle platoon system with no external energy input. A_1, A_2, A_3, A_m represent the agents corresponding to the vehicle in the vehicle platoon system. In this model, K is a specially designed nonlinear spring that also acts as an energy storage element. c represents a damper, which is an energy-consuming element whose rate of energy consumption depends on the velocity difference between agents. The storage element K is assigned specific storage limits $E_{max} + e_1$, where E_{max} denotes the initially defined energy of the entire system, including the kinetic energy of agents and the potential energy already stored in K. And e_1 is a constant to ensure that the actual energy storage of the spring does not exceed the maximum value. The energy actually stored in K is a specific function of the distance between the agents. When there is a velocity difference between agents, the energy consuming element c will keep consuming energy. According to the most fundamental laws of thermodynamics, in the absence of external energy input, the system's total energy will not increase and may decrease due to the presence of energy-consuming elements. The rest of the energy in the system consists of the energy stored in the spring and the kinetic energy of the agent, which are dynamically converted to each other.

According to the conditions mentioned above, since the system's total energy is always less than or equal to the initial energy of the system, the actual energy stored by the spring can never reach its limit. This conclusion means that the stretch and compression of the spring will not exceed the limited length. In addition, the stable state of the system is that the energy storage of the spring is 0, and the energy consumption of the energy-consuming element is also 0. The above conclusion corresponds to the vehicle platoon system, the distance between vehicles will not be less than the minimum allowable distance, nor will the communication connection be disconnected. The vehicle platoon converges to a state where the velocities of the vehicles are consistent, and the distance between the vehicles are set as expected.

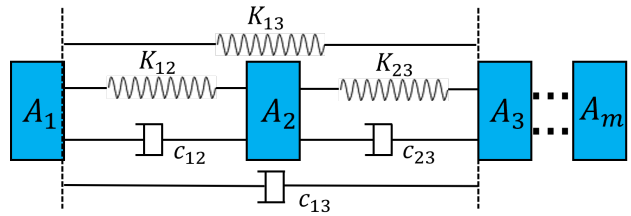


Fig. 2. A spring-damper energy system.

B. Distributed Cooperative Control Protocol

Based on the energy analysis in Section III.A, a proposed distributed control protocol is designed as follows

$$\begin{aligned}u_i = &-\sum_{j\in\mathcal{N}_i} \nabla x_i V_{ij} \left| \sum_{j\in\mathcal{N}_i} a_{ij}(v_i - v_j) \right| - \beta \sum_{j\in\mathcal{N}_i} a_{ij}(v_i - v_j) \\ &- \frac{1}{2}\Big(\sum_{j\in\mathcal{N}_i\cup\{l\}} \nabla_{x_i} V_{ij}\Big) - h_i(v_i - v_0),\end{aligned} \tag{8}$$

where $h_i(t) = \begin{cases} 1 & i \in \mathcal{N}_l(t) \\ 0 & \text{others} \end{cases}$, β is control gain, $\mathcal{N}_l$ denotes the set of neighbours of the leading vehicle. $\beta(v_i - v_j)$, and $v_i - v_0$ correspond to the damping energy dissipation function in the energy model. V_{ij} is the interaction potential function between vehicles, corresponding to the spring energy function in the energy model. The specific form of the interaction potential function in this control protocol is obtained as follows:

$$\begin{aligned}V_{ij}(\|x_{ij}\|) = &\frac{(\|x_{ij} - L_j\| - \hat{S}_{ij} + L_j)^2(\rho - \|x_{ij}\|)}{\|x_{ij} - L_j\| + \frac{(\hat{S}_{ij} - L_j)^2(\rho - \|x_{ij}\|)}{c_1 + \Psi_{max}}} \\ &+ \frac{\|x_{ij} - L_j\|\left(\|x_{ij}\| - \hat{S}_{ij}\right)^2}{(\rho - \|x_{ij}\|) + \frac{\|x_{ij} - L_j\|(\rho - \hat{S}_{ij})^2}{c_2 + \Psi_{max}}},\end{aligned} \tag{9}$$

where $\hat{S}_{ij}$ is given by (2), L_j is the length of vehicle j. Ψ_{max} is the maximum of the system energy function, which is defined as follows

$$\Psi_{max} = \frac{m^2 + m}{2} V_{max} + \frac{1}{2} \sum_{i=1}^{m} \left(v_{max} - v_0(0)\right)^2, \tag{10}$$

where $V_{max} = \max\{V(\xi_1), V(\rho - \xi_2)\}$. ξ_1 and ξ_2 are delay constants, used to ensure the stability of the communication connection. m is the maximum number of vehicles that can communicate with vehicle i.

To define the maximum interaction force of vehicle due to the potential field as f. When $\lambda_2((\beta Q + 2PH)(t)) > 4mf$ is satisfied, the platoon system is asymptotically stable. Where $P = \operatorname{diag}\{p_i\} \in \mathbb{R}^{N\times N}$, $p = [p_1, p_2, \ldots, p_N]$ is the left eigenvector corresponding to the zero eigenvalue of $L(\mathcal{G})$. $H = \operatorname{diag}\{h_1(t), h_2(t), \ldots, h_N(t)\}$, and f is the maximum interaction force of vehicle due to the potential field. Q is the Laplace matrix of graph $\bar{\mathcal{G}}$, the weighted mirror graph of a connected directed graph $\mathcal{G}$.

Let the follower's position and speed deviation from the leading vehicle be $\tilde{x}_i = x_i - x_0$ and $\tilde{v}_i = v_i - v_0$. Therefore, we have

$$
\begin{aligned}
\dot{\tilde{x}}_i &= \tilde{v}_i \\
\dot{\tilde{v}}_i &= -\sum_{j\in\mathcal{N}_i} \nabla\tilde{x}_i\tilde{V}_{ij}\left|\sum_{j\in\mathcal{N}_l} a_{ij}(\tilde{v}_i-\tilde{v}_j)\right| \\
&\quad -\beta\sum_{j\in\mathcal{N}_l} a_{ij}(\tilde{v}_i-\tilde{v}_j) \\
&\quad -\frac{1}{2}(\sum_{j\in\mathcal{N}_l\cup\{l\}}\nabla_{\tilde{x}_i}\tilde{V}_{ij}) - h_i\tilde{v}_i.
\end{aligned} \tag{11}
$$

Define the following non-negative energy function:

$$
\Psi = \sum_{i=1}^{N} p_i \sum_{j\in\mathcal{N}_i\cup l}\tilde{V}_{ij}(\|\tilde{x}_{ij}\|) + \tilde{v}^{\mathrm{T}}P\tilde{v}, \tag{12}
$$

where $\tilde{v} = [\tilde{v}_1,\ldots,\tilde{v}_N]^{\mathrm{T}}$.

Suppose $\mathcal{G}(t)$ will change its connection topology at t_e, $e = 1, 2, \ldots$, and the system connection topology $\mathcal{G}(t_e)$ will not change during $[t_e, t_{e+1})$. It's easy to verify that $\tilde{V}_{ij}$ is finite according to (9). Hence, $\Psi(t_e)$ is bounded. Take the derivative of the function in the interval $[t_e, t_{e+1})$:

$$
\begin{aligned}
\dot{\Psi} &= \sum_{i=1}^{N}\tilde{v}_i^{\mathrm{T}}p_i\sum_{j\in\mathcal{N}_l\cup\{l\}}\nabla\tilde{x}_i\tilde{V}_{ij} \\
&\quad + 2\tilde{v}^{\mathrm{T}}P\left(\begin{aligned}&-\beta L\tilde{v}-\mathrm{diag}\left\{\nabla\tilde{x}_i\tilde{V}_i\right\}|L\tilde{v}| \\ &-\frac{1}{2}\nabla\tilde{V}-H\tilde{v}\end{aligned}\right),
\end{aligned} \tag{13}
$$

where

$$
\begin{cases}
\tilde{V}_i = \sum_{j\in\mathcal{N}_i}\tilde{V}_{ij} \\
\nabla\tilde{V} = \sum_{j\in\mathcal{N}_l\cup\{l\}}\nabla_{\tilde{x}_i}\tilde{V}_{ij}.
\end{cases}
$$

(13) can be simplified as

$$
\dot{\Psi} = 2\tilde{v}^{\mathrm{T}}P\left(-\beta L\tilde{v} - \mathrm{diag}\left\{\nabla\tilde{x}_i\tilde{V}_i\right\}|L\tilde{v}| - H\tilde{v}\right). \tag{14}
$$

We can obtain the following inequality

$$
\left|\nabla\tilde{x}_i\tilde{V}_i\right| = \left|\nabla\tilde{x}_i\sum_{j\in\mathcal{N}_i}\tilde{V}_{ij}\right| \le f. \tag{15}
$$

Hence, substituting it to (14), we have

$$
\begin{aligned}
\dot{\Psi} &\le -2\tilde{v}^{\mathrm{T}}P\left(\beta L + H\right)\tilde{v} + 2f\left\|\tilde{v}\right\|\left\|P\right\|\left\|L\tilde{v}\right\| \\
&\le -\tilde{v}^{\mathrm{T}}\left(\beta Q + 2PH\right)(t)\tilde{v} + 2f\left\|\tilde{v}\right\|\left\|P\right\|\left\|L\right\|\left\|\tilde{v}\right\|.
\end{aligned} \tag{16}
$$

According to the definition of Laplace matrix, we can get

$$
L(\mathcal{G}) = \mathrm{diag}\left\{d_i\right\} - A,
$$

where A and $diag\left\{d_i\right\}$ are, respectively, the adjacency matrix and in-degree matrix of graph $\mathcal{G}$. According to the communication rules defined in Fig. 1, we can determine that the adjacency matrix of the topology of vehicle platoon connection is a strict lower triangular matrix,

$$
A = \begin{bmatrix} 0 & \cdots & \cdots & 0 \\ 1 & \ddots & & \vdots \\ \vdots & 1 & \ddots & \vdots \\ * & \cdots & 1 & 0 \end{bmatrix}, \tag{17}
$$

where $*$ indicates that the value is uncertain and determined by the connection topology at a specific time. It may be 0 or 1. And the $\mathrm{Max}\left\{d_i\right\} = m$. Hence, $\|L\| \le 2m$. Then (16) can be further rewritten as:

$$
\begin{aligned}
\dot{\Psi} &\le -\tilde{v}^{\mathrm{T}}\left(\beta Q + 2PH\right)(t)\tilde{v} + 4mf\left\|\tilde{v}\right\|^2 \\
&\le -\left(\lambda_2\left(\beta Q + 2PH\right)(t) - 4mf\right)\left\|\tilde{v}\right\|^2.
\end{aligned} \tag{18}
$$

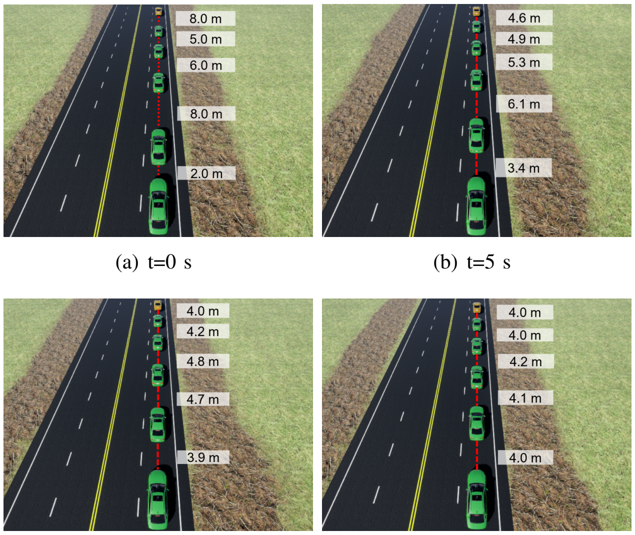
Substituting the initial condition $\lambda_2((\beta Q + 2PH)(t)) > 4mf$, it gives $\dot{\Psi}(t) \le 0, \forall t \in [t_e, t_e + 1)$. Therefore, the system is asymptotically stable.

According to the topology network of the platoon, the control input of the controlled vehicle is only affected by the vehicle in front. And the upper limit of the number of individual vehicles that directly affect the control input of the controlled vehicle is m. The spring-damped energy model shows that any platoon system consisting of less than or equal to m vehicles is stable and can converge to the desired steady state. For a platoon of N+1 vehicles, any individual vehicle other than the leading vehicle can form an energy system as shown in the Fig. 2 with the vehicle in front of it . As a result, every following vehicle in the entire vehicle platoon system will be synchronised with the vehicle in front while maintaining a safe following distance from the vehicle in front, as analysed in Section A. In our theory, we abstract the communication topological connection as a spring energy storage element in the energy model and the velocity difference as a damped energy dissipation element. Therefore, as long as the connectivity of the communication topology connection is guaranteed, the stability of the vehicle platoon system can be ensured. According to our definition of the communication topology, the presence of on-board sensors ensures that the vehicle platoon is able to form at least the simplest directed connected graph. Therefore, when V2V communication is lost, the proposed distributed cooperative controller still ensures the stability of the vehicle platoon and achieves the control objectives.

IV. Evaluation

In this section, we mainly verify the effectiveness of the algorithm in dynamic topology scenarios and fixed topology scenarios. MATLAB and Unreal Engine are utilized for simulation experiments. The parameters used in the simulation experiments are given as follows:

- Five follower vehicles and one leader vehicle are considered in the simulation experiments.
- The communication range of a vehicle $\rho = 17$ m, and a communication link can be established between vehicles once the distance is less than 17 m.



(a) t=0 s (b) t=5 s

(c) t=15 s (d) t=40 s

Fig. 3. Process of the vehicle platooning task under fixed network topology. The yellow car denotes the leader, and green cars represent the followers.

- The desired following distance is 4 m, and the vehicle body length is 4 m.
- The leader's speed is 20 m/s and the initial speed of each following vehicle is obtained randomly in range $[15, 20]$ m/s.
- The sampling time is 0.025 s, control gain $\beta = 10$, $\xi_1 = \xi_2 = 1$ m, $c_1 = c_2 = 2$. Furthermore, we determine the Ψ_{max} according to the (10), $\Psi_{max} = 10$.

A. Case 1: Fixed Topology

In this scenario, we verify the effectiveness of the algorithm for fixed network topology. Here, a worst scenario for fixed topology is considered: V2V communication is completely disabled and the topological connection between vehicles is only achieved by the on-board radar, i.e., a vehicle can only acquire the position and speed information of the closest vehicle ahead. The vehicle platoon in CACC state will degrade to ACC state. In this case, the connection topology of the vehicle platoon system forms the simplest connected graph. With this fixed communication topology, Fig. 3 illustrates the process of vehicle platooning. In addition, the results shown in Fig. 4 and Fig. 5 demonstrate that the speed and following distance of the vehicle platoon still converge to the desired values although the CACC completely degrades to an ACC. This scenario is of great practical importance. When the vehicle platoon is subject to network attacks or communication blocking, the energy model and distributed control protocol proposed can ensure that the vehicle platoon continues to converge safely to a steady state.

B. Case 2: Dynamic Topology

In this scenario, we verify the effectiveness of the algorithm for dynamic network topology. We assume that the vehicles will disconnect or establish new communication connections in real-time, depending on the status of the surrounding vehicles. Since the number of topological

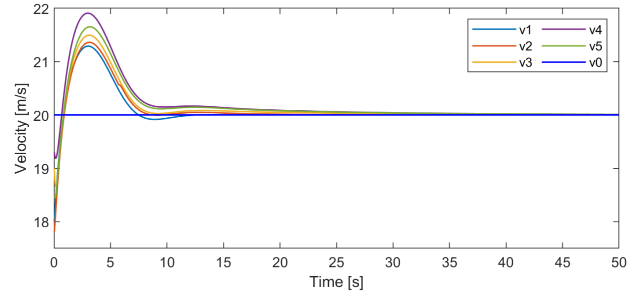


Fig. 4. Time-variation of the velocities of the vehicle platoon without V2V communication.

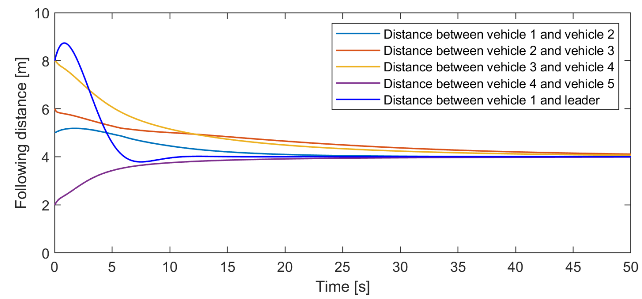


Fig. 5. Time-variation of the vehicle following distances without V2V communication.

connections characterises the system's stability to a certain extent, in the case of dynamic topology, the increase of the system communication connections is beneficial for the stability of the vehicle platoon system.

Fig. 6 indicates the velocity changes of vehicle platoon for dynamic network topology. The result shows that the velocity of every follower can converge to the velocity of the leader. Meanwhile, the following distance will also converge to the desired value, which consists of safe following distance and body length of the vehicle. From Fig. 7, we can observe that the following distance is always greater than 2 m, which means the vehicle will never be in a collision with its neighbours. In addition, the communication topology of the vehicle platoon changes dynamically as the following distance changes. As can be seen in Fig. 8, the initial number of connections in the platoon is 5, and after t=22 s, the number of connections in the platoon rises to 9 connections. This also means that the convergence speed and stability of the whole platoon system is improved. Finally, there is an apparent phenomenon of a sudden change in the speed of vehicle as follower vehicles are tracking the leader vehicle. According to our analysis of the experimental results, the abrupt change in speed is mainly caused by new communication connections.

V. Conclusion

In this paper, a Spring-Damper Energy System (SDES) was proposed to construct the vehicle platoon system, and a distributed cooperative control algorithm was designed to realise the effective cruise control of the autonomous vehicles. The simulation results proved that the proposed

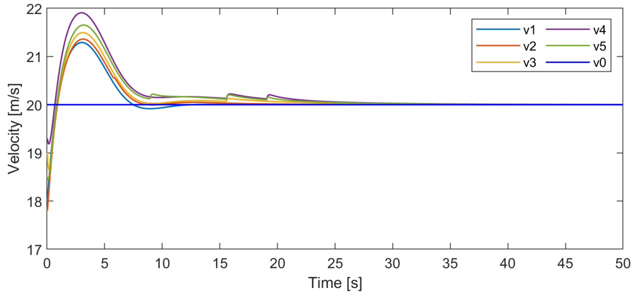


Fig. 6. Time-variation of the velocities of the vehicles, where v_0 represents the velocity of the leader and v_1-v_5 represent the velocities of 5 followers.

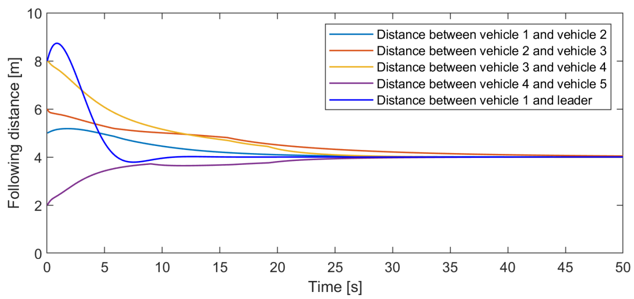


Fig. 7. Time-variation of the vehicle following distances, where the length of the vehicle is defined as 4 m and the desired distance between the vehicle head and the rear of the vehicle in front of it is set as 4 m.

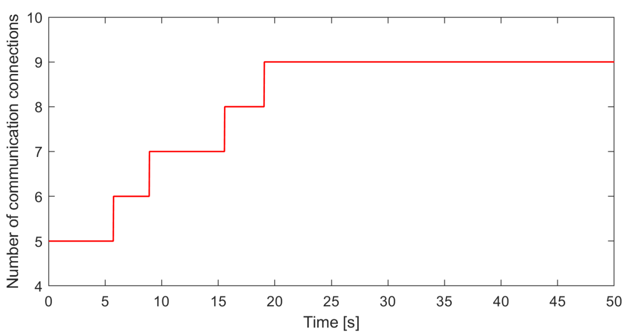


Fig. 8. Time-variation of the number of communication connections.

algorithm ensures safe following distances within the platoon and achieves vehicle speed consistency. In addition, the designed algorithm ensured that in the event of V2V communication loss, the vehicle platoon can still rely on its on-board sensors to maintain a stable and safe ride. For the future work, we will continue to study and optimise this approach in depth, which include considering overtaking scenarios and merging of different vehicle platoons. We note that in the dynamic topology connection scenario, a slight abrupt change in vehicle speed occurs when a new communication connection appears in the platoon system. Machine learning and optimisation techniques may need to be integrated to the proposed controller design to further improve the trajectory tracking performance.

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