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A Synchronization Approach for Achieving Cooperative Adaptive Cruise Control Based Non-Stop Intersection Passing

Zhe Liu, Huanshu Wei, Hanjiang Hu, Chuanzhe Suo, Hesheng Wang, Haoang Li, and Yun-Hui Liu

Abstract— **Cooperative adaptive cruise control (CACC) of intelligent vehicles contributes to improving cruise control performance, reducing traffic congestion, saving energy and increasing traffic flow capacity. In this paper, we resolve the CACC problem from the viewpoint of synchronization control, our main idea is to introduce the spatial-temporal synchronization mechanism into vehicle platoon control to achieve the robust CACC and to further realize the non-stop intersection control. Firstly, by introducing the cross-coupling based space synchronization mechanism, a distributed control algorithm is presented to achieve the single-lane CACC in the presence of vehicle-to-vehicle (V2V) communications, which enables autonomous vehicles to track the desired platoon trajectory while synchronizing their longitudinal velocities to keeping the expected inter-vehicle distance. Secondly, by designing the enter-time scheduling mechanism (temporal synchronization), a high-level intersection control strategy is proposed to command vehicles to form a virtual platoon to pass through the intersection without stopping. Thirdly, a Lyapunov-based time-domain stability analysis approach is presented. Compared with the traditional string stability based approach, the proposed approach guarantees the global asymptotical convergence of the proposed CACC system. Experiments in the small-scale simulated system demonstrate the effectiveness of the proposed approach.**

I. INTRODUCTION

Platoon control of autonomous vehicles has been investigated extensively since the 1990s [1], [2] and several practical testing systems have been developed in recent years [3]–[5]. Forming a platoon contributes to increasing traffic flow capacities and saving energies. Based on Adaptive Cruise Control (ACC) approach and vehicle-to-vehicle (V2V) / vehicle-to-infrastructure (V2I) communication technology, Cooperative Adaptive Cruise Control (CACC) is expected to achieve more robust and reliable platoon control performance [3], [4].

Intersection handling is one of the most challenging problems for intelligent vehicles [7]–[9] and inevitable stop-and-go patterns during intersection passings may cause shock waves propagated in traffic flows and result in traffic jams [2]. With traffic management and vehicle scheduling, CACC technique can be utilized to realize non-stop intersection passing, which will greatly increase the traffic efficiency and save energies consumed during decelerations and accelerations in stop-and-go patterns.

In this paper, we introduce the CACC approach into resolving the non-stop intersection passing control problem of autonomous vehicles. Our main idea is to transform the non-stop intersection passing control problem into a CACC problem with virtual platoons, then introduce the spatial-temporal synchronization mechanism to achieve robust CACC and thus realizing the non-stop intersection passing. More specifically, we firstly introduce a space synchronization mechanism to build the CACC system. The information of the preceding and succeeding vehicles is considered to imitate human driving behaviors and achieve robust platoon control. Secondly, we design an enter-time scheduling mechanism to achieve the temporal synchronization of all the vehicles near the intersection, i.e., assembling them into a virtual platoon. Then the previously established CACC approach can be directly utilized to coordinate the motion of each vehicle in the virtual platoon and the non-stop intersection passing control can be achieved.

A. Related Work

1) Intersection Planning and Control:

Intersection handling is one of the most challenging issues in current self-driving systems and most previous accidents occurred at intersections [7]–[9]. Traditional researches mainly focus on predicting the intention and motion trajectory of the related vehicles and optimizing the decision making system to avoid collisions [7], [8], [13]. However, these algorithms have not taken advantages of the V2V / V2I technologies and system-level autonomy of the vehicle platoon, and stop-and-go behaviors during intersection passings will increase the energy consumptions and may cause traffic jams [2].

Managing the traffic flow and scheduling the vehicle enter-time can be achieved by developing the traffic management center which receives vehicle information and sends scheduling decisions through communication networks. Based on which, the intersection passing time of each vehicle can be coordinated and non-stop intersection passing can be realized [9]. However, these researches mainly focus on the route planning and intersection scheduling problem, and are based on the assumptions of prefect individual vehicle motion control performance. External disturbances and motion control

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Z. Liu, H. Wei, C. Suo, H. Li and Y.-H. Liu are with the Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong.

H. Hu is with the Department of Automation, Shanghai Jiao Tong University, China.

H. Wang is with Department of Automation, Key Laboratory of System Control and Information Processing of Ministry of Education, Key Laboratory of Marine Intelligent Equipment and System of Ministry of Education, Shanghai Jiao Tong University, Shanghai 200240, China. H. Wang is also with Beijing Advanced Innovation Center for Intelligent Robots and Systems, Beijing Institute of Technology, China.

un-accuracies may result in an unstable coordination system, and lead to vehicle collisions.

2) Vehicle Cruise Control:

In the past decades, researchers have developed numerous car-following models (CRFs) in order to model human driving behaviors, a review of the past 50 years can be found in [1]. Among these, Intelligent Driver Model (IDM) [1] and its extensions have been widely used to model human behaviors and to achieve autonomous cruise control [2]. However, testing results presented in [6] showed that IDM controller has significant shortcomings in the presence of preceding vehicle speed changes.

In recent years, in order to achieve a safe and comfortable driving experience, ACC has been investigated actively and commercial systems have been developed [6]. ACC overcomes the large response delay and distance error of IDM controllers, however, it may amplify preceding vehicle velocity changes and lead to upstream shock-waves. More recently, thanks to the rapid development of V2V / V2I communication technologies, CACC has been extensively studied, which has been proved to have the advantages of decreasing fuel consumptions and maintaining stability under short inter-vehicle distances [3]. However, in most existing work [3]–[5], only the information of preceding and leading vehicles is considered, disturbances in succeeding vehicles can not be responded by the whole platoon in a synchronous manner, thus reducing the efficiency and robustness of the CACC system. Another problem is that, in existing work [3]–[5], the current acceleration of the preceding vehicle is required to achieve the CACC functionality. Compared with the velocity and position information, vehicle acceleration usually changes rapidly and can not be measured accurately or obtained in real-time. This requirement will impact the implementation feasibility of the existing controllers.

3) System-Level Autonomy and Stability Analysis:

Sudden velocity changes of the preceding vehicle may cause upstream shock-waves and form traffic jams [2]. This property can be analyzed by the string stability approach [11]. A vehicle platoon is string stable if changes of the velocity of preceding vehicles will be attenuated in the response of the following vehicles [3].

Both the vehicle-level and system-level string stability conditions are presented in [2] and based on which, an optimal controller is further proposed which enables a single autonomous vehicle to stabilize a string of human driving vehicles. However, in most existing work [2]–[4], frequency domain analysis of the error transfer function is utilized to construct the string stability approach. This approach can only guarantee the local stability of the CACC system through model linearization near the work point. In order to utilize these approaches, the uniform flow equilibrium of the CACC system should be global stable. Or an additional controller is required to bring the system to the neighborhood of the equilibrium [2] before the existing CACC approaches can be implemented. These will greatly limit the practical applications of the existing CACC approaches. Recently, neural network based methods have been utilized in transportation systems to achieve adaptive control without linearizing operations [14], however, the effectiveness of this type of approaches in CACC systems has not been validated yet.

B. Main Contribution

The main contributions of this paper can be summarized as follows:

Firstly, a novel CACC approach is presented in this paper by introducing the synchronization framework. The proposed approach ensures that the position error of each vehicle converges to zero in a synchronous manner, i.e., the desired inter-vehicle distance can be maintained and the robustness to external disturbances can be improved.

Secondly, we transform the non-stop intersection passing control problem of autonomous vehicles into a CACC problem by introducing the virtual platoon concept. The proposed spatial-temporal synchronization mechanism regulates the intersection enter-time of the vehicles in the virtual platoon and simultaneously coordinate their motions to avoid collisions. Then based on the proposed CACC approach, the reliability and robustness of the intersection coordination system can be guaranteed.

Thirdly, a time-domain stability analysis approach is presented based on the Lyapunov method. Compared with the string stability approach, the proposed approach guarantees the global convergence of the CACC system even under substantial initial errors, thus ensuring the applicability of the proposed approach in practical implementations.

The rest of this paper is organized as follows: Section II describes the overall system structure, Section III presents the detailed methods of the proposed CACC based non-stop intersection passing control system. Simulations and real experiments are proposed in Section IV and Section V respectively. Finally, the conclusion and future work are described in Section VI.

II. System Structure

Similar to most existing work [2]–[6], we consider the single-lane CACC task. The longitudinal control and lateral control can be decoupled [2]–[6] and we restrict this work to the longitudinal control problem, i.e., we focus on designing the acceleration control law of each vehicle. We assume that relative velocities of the preceding and succeeding vehicles as well as the inter-vehicle distances can be measured or obtained in real-time, and there exists a traffic management center which collects the state of each vehicle and formulates the virtual platoon which defines the intersection passing order (enter-time). Figure 1 shows the overall structure of the proposed system.

Based on the proposed CACC controller, the onboard motion control system enables each vehicle to keep synchronous velocity and desired inter-vehicle distance with its neighbors in the virtual platoon, thus achieving the non-stop intersection passing task.

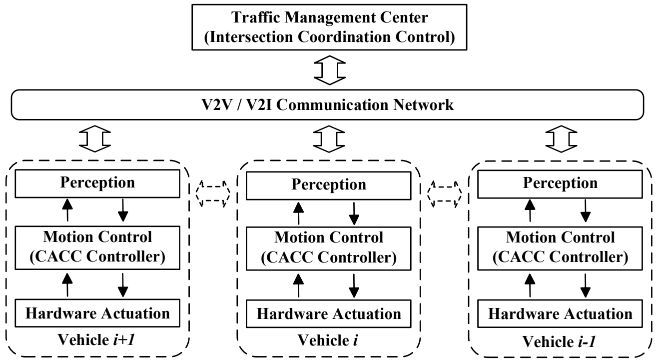

Fig. 1. Overall system structure.

III. CACC BASED NON-STOP INTERSECTION PASSING CONTROL

A. Synchronization Approach for CACC

Consider N autonomous vehicles driving in a platoon, as shown in Figure 2, where x_i and v_i represent the longitudinal position and velocity of each vehicle i, h_i is the inter-vehicle distance between vehicle $i-1$ and vehicle i. x_i^d is the desired position of vehicle i, which can be calculated from the desired platoon trajectory, or from the preceding vehicle position x_{i-1} and the desired inter-vehicle distance h_i^d. Please note that h_i^d can be either a constant [2], [10] or a time-varying form [3], [4]. If h_i^d is an identical constant, i.e., $h_i^d = h_j^d = h^*$, we have $\dot{x}_i^d = \dot{x}_j^d = v^d$ and $\ddot{x}_i^d = \ddot{x}_j^d = \dot{v}^d$, where v^d and $\dot{v}^d$ represent the desired platoon velocity and acceleration. Otherwise, we denote $\dot{x}_i^d = v_i^d$ and $\ddot{x}_i^d = \dot{v}_i^d$. v_i^d is assumed to be uniformly continuous. We ignore the vehicle length for simplicity, which can be considered in h_i or h_i^d in implementations.

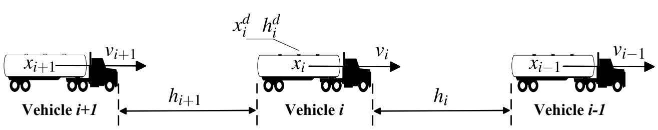

Fig. 2. CACC control structure of a vehicle platoon.

By defining the position error of each vehicle i as $\tilde{x}_i = x_i - x_i^d$ and position synchronization error $\varepsilon_i = \tilde{x}_{i-1} - \tilde{x}_i$, we have

$$\varepsilon_i = (x_{i-1} - x_i) - (x_{i-1}^d - x_i^d) = h_i - h_i^d = \tilde{h}_i, \tag{1}$$

$$\dot{\varepsilon}_i = \dot{h}_i - \dot{h}_d = v_{i-1} - v_i - \dot{h}_i^d. \tag{2}$$

Obviously, the CACC problem has been transformed into a motion synchronization control problem, the control objective is to converge $\tilde{x}_i$, ε_i and $\dot{\varepsilon}_i$ of each vehicle i to zero simultaneously.

In order to achieve motion synchronization, we introduce the cross-coupling approach [15] to define the coordination error

$$\kappa_i = k_h(\varepsilon_{i+1} - \varepsilon_i) = k_h(\tilde{h}_{i+1} - \tilde{h}_i). \tag{3}$$

Then a coupled error s_i can be defined as the combination of $\tilde{x}_i$, $\dot{\tilde{x}}_i$, and κ_i of each vehicle i, where

$$s_i = \dot{\tilde{x}}_i + k_p\tilde{x}_i + \kappa_i = \dot{\tilde{x}}_i + k_p\tilde{x}_i + k_h(\tilde{h}_{i+1} - \tilde{h}_i). \tag{4}$$

Finally, we design the following CACC acceleration control law

$$a_i = \dot{v}_i^d - k_p\dot{\tilde{x}}_i - \dot{\kappa}_i - k_{si}s_i, \tag{5}$$

where k_p, k_h and k_{si} are positive control gains, κ_i is defined in (3), and $\kappa_1 = k_h\tilde{h}_2$, $\kappa_N = -k_h\tilde{h}_N$.

The proposed controller (5) leads to the close-loop dynamics $\dot{s}_i + k_{si}s_i = 0$, which implies that s_i and $\dot{s}_i$ converge to zero exponentially. Since $s_i \to 0$, we have

$$\begin{aligned} \dot{\tilde{x}}_i &= -k_p\tilde{x}_i - k_h(\tilde{h}_{i+1} - \tilde{h}_i) \\ &= -k_p\tilde{x}_i - k_h[(\tilde{x}_i - \tilde{x}_{i+1}) - (\tilde{x}_{i-1} - \tilde{x}_i)] \end{aligned} \tag{6}$$

By defining $\tilde{x} = [\tilde{x}_1, \tilde{x}_2, ..., \tilde{x}_N]^T$, $K_p = diag\{k_p\}_{N\times N}$, $K_h = diag\{k_h\}_{N\times N}$, and the cross-coupling topology matrix as follows

$$\phi_{N\times N} = \begin{bmatrix} -1 & 1 & 0 & & ... & & 0 \\ 1 & -2 & 1 & & & & \\ & & & \ddots & & & \\ & & & & 1 & -2 & 1 \\ 0 & & ... & & 0 & 1 & -1 \end{bmatrix},$$

we have the following error dynamics

$$\dot{\tilde{x}} = -K_p\tilde{x} + K_h\phi\tilde{x}. \tag{7}$$

B. CACC Formulation of Non-Stop Intersection Passing

We introduce the virtual platoon concept [9] to coordinate the enter-time of each vehicle near the intersection. In order to solve the intersection coordination problem, the CACC system formulated in Section III should be re-defined as follows:

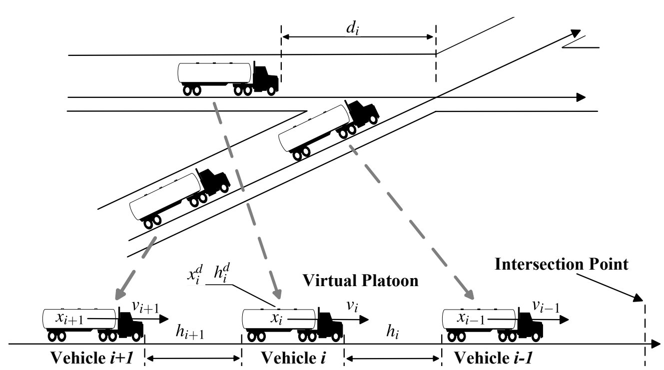

Fig. 3. Virtual platoon based CACC problem for intersection coordination.

Consider an intersection with two single-lane roads and N vehicles (here we utilize the batch control concept and only consider the vehicle of which the distance to the intersection is smaller than a threshold, i.e., $d_i < D$). As shown in Figure 3, in order to schedule the enter-time of each vehicle, all the vehicles are assembled in a virtual platoon and the order of each vehicle is determined by its distance to the intersection center. The leader vehicle (vehicle 1) is the one which has the nearest distance to the intersection center, and we assume that it has a desired velocity v_1^d and is controlled to track its desired trajectory individually. Then $x_i = D - d_i$ and $x_i^d = x_1^d - \sum_{j=2}^{i} h_j^d$ represent the virtual position and desired virtual position of vehicle i in the virtual platoon. If $h_i^d = h_j^d = h^*$, $x_i^d = x_1^d - (i-1)h^*$. The definition of other variables is the same as Section III.

Based on the above definitions, the non-stop intersection passing control problem has been transform into the CACC control problem with the virtual vehicle platoon defined above. Then the proposed CACC approach in Section III can be used to solve this problem.

It is obvious that if the virtual position error $\tilde{x}_i$ and synchronization error ε_i of each vehicle converge to zero simultaneously, the enter-time can be coordinated and the non-stop intersection passing can be achieved.

C. Stability Analysis

We first introduce two lemmas which will be used in the proposed stability analysis.

Lemma 1: Each vehicle in the platoon keeps the desired inter-vehicle distance with the preceding vehicle, i.e., $\varepsilon_i \to 0$, $h_i \to h_d$, if $M\tilde{x} \to 0$, where

$$M_{(N-1)\times N} = \begin{bmatrix} 1 & -1 & & & \\ & 1 & -1 & & \\ & & & \ddots & \\ & & & 1 & -1 \end{bmatrix}.$$

Proof: Combining the definition of ε_i, M and $\tilde{x}$, this lemma can be proved directly. ■

Lemma 2: (see [16]) For a topology matrix $\psi_{N,N} = \{\psi_{ij}\}$, if $\sum_{j=1}^{N} \psi_{ij} = 0$, $i = 1,...,N$, then $M\psi = HM$, where $H = M\psi L$,

$$L = \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ 0 & 1 & 1 & \dots & 1 \\ & & \ddots & & 1 \\ & & \dots & 1 & 1 \\ 0 & 0 & \dots & 0 & 1 \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix}_{N\times(N-1)},$$

and M is defined in Lemma 1.

Then we present a sufficient condition which ensures the global convergence of the proposed system as follows:

Theorem 1: The proposed CACC system is globally asymptotically stable, i.e., the position error $\tilde{x}_i$, inter-vehicle distance error $\tilde{h}_i$ and the relative velocity error $\dot{\tilde{h}}_i$ converge to zero asymptotically, if $sym(-\bar{K}_p + \bar{K}_h H) < 0$, where $\bar{K}_p = diag\{k_p\}_{(N-1)\times(N-1)}$, $\bar{K}_h = diag\{k_h\}_{(N-1)\times(N-1)}$, $sym(A) = A + A^T$, and H is defined in Lemma 2.

Proof: Defining the Lyapunov function $V = \tilde{x}^T M^T M \tilde{x}$, where M is defined in Lemma 1, we have

$$\dot{V} = -2\tilde{x}^T M^T M K_p \tilde{x} + 2\tilde{x}^T M^T M K_h \phi \tilde{x}.$$

According to the definition of ϕ and Lemma 2, we have $M\phi = HM$, and according to the definition of K_p, K_h, $\bar{K}_p$, $\bar{K}_h$, and M, we have $MK_p = \bar{K}_p M$ and $MK_h = \bar{K}_h M$. Then

$$\begin{aligned} \dot{V} =& -2\tilde{x}^T M^T \bar{K}_p M \tilde{x} + 2\tilde{x}^T M^T \bar{K}_h H M \tilde{x} \\ =& -2\tilde{x}^T M^T (\bar{K}_p - \bar{K}_h H) M \tilde{x} < 0. \end{aligned}$$

Since $\dot{\tilde{x}}$ is bounded, $\dot{V}_i$ is uniformly continuous, then from the Barbalat's Lemma we have $\dot{V}_i \to 0$, which implies $M\tilde{x} \to 0$. According to Lemma 1, $\varepsilon_i \to 0$, $\tilde{h}_i = h_i - h_d \to 0$. Then from (6), we have $\dot{\tilde{x}}_i + k_p \tilde{x}_i = 0$, which implies that $\dot{\tilde{x}}_i \to 0$, $\tilde{x}_i \to 0$, and $\dot{\tilde{h}}_i = \dot{\tilde{x}}_{i-1} - \dot{\tilde{x}}_i \to 0$.

The proof is completed. ■

D. Implementations and Discussions

From (1)-(4), the proposed controller (5) can be re-wrote as:

$$\begin{aligned} a_i =& \dot{v}_i^d - (k_p + k_{si})\dot{\tilde{x}}_i - k_p k_{si} \tilde{x}_i \\ & - k_h(\dot{\tilde{h}}_{i+1} - \dot{\tilde{h}}_i) - k_h k_{si}(\tilde{h}_{i+1} - \tilde{h}_i). \end{aligned} \quad (8)$$

Since $\tilde{h}_{i+1} - \tilde{h}_i = (h_{i+1} - h_i) - (h_{i+1}^d - h_i^d)$, we have

$$\begin{aligned} a_i =& \dot{v}_i^d - (k_p + k_{si})\dot{\tilde{x}}_i - k_p k_{si} \tilde{x}_i + k_h(\dot{h}_{i+1}^d - \dot{h}_i^d) \\ & + k_h k_{si}(h_{i+1}^d - h_i^d) - k_h(\dot{h}_{i+1} - \dot{h}_i) - k_h k_{si}(h_{i+1} - h_i). \end{aligned}$$

We can find that, in addition to the desired information and its own states, each vehicle only needs to measure the relative velocities and the inter-vehicle distances to its two neighbors. This guarantees the feasibility of implementing the proposed approach in real applications.

Remark 1: In the proposed approach, both information of the preceding and succeeding vehicles is considered in controller design, then based on the cross-coupling topology, the disturbance in one vehicle will be respond simultaneously by all vehicles in the platoon. what's more, $M\tilde{x} \to 0$ implies that the position error of each vehicle converges to zero in a synchronous manner, i.e., the desired inter-vehicle distance can be maintained. So introducing the synchronization approach contributes to improve the robustness of the CACC system.

Remark 2: The proposed approach guarantees the global convergence of the CACC system, thus we relax the assumption in string-stability approaches and do not need an additional controller to bring the system to the neighborhood of the work point.

Remark 3: Since information of virtual neighbors in the virtual platoon can not be directly measured by vehicle i and can only be obtained through V2V / V2I communications, the communication delays between the traffic management center and vehicles may affect the reliability of the intersection coordination system. However, with the rapid development of the V2V / V2I communication technologies, typically the communication delay and the response delay of the hardware vehicle platform are totally different in size, so most of researches ignore the communication delay [9]. In this paper, we present simulations to validate the effectiveness of the proposed CACC approach in the presence of communication delays. Simulation results in Section IV show that the introduction of communication delays only causes some response delays and does not affect the final convergence of the CACC system. If the inter-vehicle distance is set to be large enough, this effect can be ignored. In the future, we will evaluate the effect of communication delays on the platoon control performance in practical applications, and consider the communication delay in system design explicitly.

IV. Simulations

We first present simulations to validate the robustness and scalability of the proposed CACC approach. In simulation 1, 15 vehicles are commanded to form a platoon with a desired time-varying velocity $v_i^d = v_r = 5 + 1.5\cos(0.075t)$ and a constant inter-vehicle distance $h_i^d = h^* = 17.5m$. Then the proposed CACC controller can be simplified as the following form:

$$a_i = \dot{v}_r - 0.3\dot{\tilde{x}}_i - 0.2\tilde{x}_i - 0.3(\dot{h}_{i+1} - \dot{h}_i) - 0.2(h_{i+1} - h_i).$$

In order to validate the effectiveness and robustness of the prooposed CACC approach in solving the virtual platoon control problem, we add a communication delay $\tau = 0.2s$, i.e.,

$$\varepsilon_i = \tilde{x}_{i-1}(t-\tau) - \tilde{x}_i(t-\tau).$$

In addition, we set the acceleration saturation limit to $|a_i| < 0.2G = 1.96m/s^2$, which is usually used in the practical ACC system to ensure the ride comfort. What's more, we add an acceleration disturbance $-1.3a_8$ to vehicle 8 (i.e., $a_{8|input} = -0.7a_8$) from $t = 55s$ to $60s$ to demonstrate the robustness of the proposed approach.

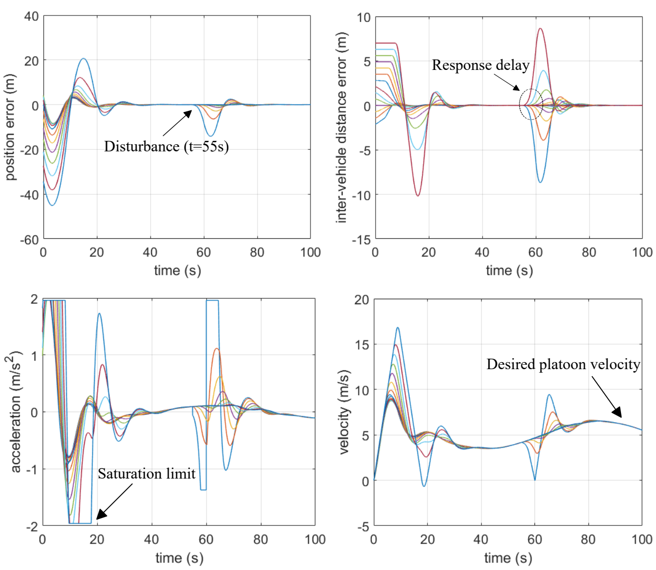

Fig. 4. Results of the simulation 1.

We set $x_1^d(0) = 0$, $x_i^d(0) = x_{i-1}^d(0) - h^*$, $x_i(0) = x_i^d - 0.02(i-8)(i-1)h^*$ and $v_i(0) = 0$, i.e., we add substantial initial errors. Results in Figure 4 show that the position error $\tilde{x}_i$, inter-vehicle distance error $\tilde{h}_i$ and velocity error $\dot{\tilde{x}}_i$ of each vehicle converge to zero simultaneously. Furthermore, external disturbances on vehicle 8 are responded by all the 15 vehicles in a synchronous manner, the preceding vehicles also slow down (from $t = 55s$ to $80s$) to wait for the disturbed vehicle to maintain the platoon. Thanks to the synchronization mechanism, the disturbed vehicle can catch up and recover in a short time. Note that the response delay in Figure. 4 results from the communication delays considered in the simulation. The results validate the effectiveness and robustness of the proposed approach in the presence of acceleration saturation limits, external disturbances, substantial initial errors and communication delays.

In simulation 2, we change the desired inter-vehicle distance into a non-unified and time-varying form $h_i^d = h_{\min} + t_{d,i}v_i$. where the leader vehicle has a time-varying velocity $v_1 = 5 + 1.5\cos(0.075t)$, and following vehicles keep the desired inter-vehicle distance to their preceding vehicles. We set $h_{\min} = 5m$, $t_{d,i} = 2.5s$, $x_1 = 5t + 20sin(0.075t)$, $\tilde{h}_i(0) = 0$, other parameters are the same as simulation 1. Then the proposed CACC controller can be transformed into the following form:

$$a_i = a_{i-1} - 0.08\dot{\tilde{x}}_i - 0.5\tilde{x}_i - 0.08(\dot{\tilde{h}}_{i+1} - \dot{\tilde{h}}_i) - 0.5(\tilde{h}_{i+1} - \tilde{h}_i).$$

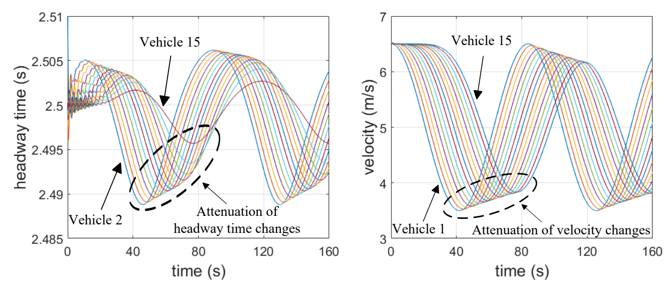

Fig. 5. Results of the simulation 2.

Results in Figure 5 show that velocity changes of the leader vehicle and headway time errors of preceding vehicles are attenuated in the response of following vehicles, these validate the stability of the proposed approach. Note that in simulation 2, the information of x_i^d is absent for the following vehicles and h_i^d is non-unified and time-varying, so the control system will not converge to an equilibrium unless the velocity of the leader vehicle keeps constant.

V. Real Experiments in Small-Scale Simulated Systems

We further conduct laboratorial experiments in small-scale simulated systems with several TurtleBot-3 Burger robots to demonstrate the practical applicability of the proposed approach.

An indoor vision positioning system is constructed to localize each vehicle in real time and a wireless communication network is established to achieve communications. Due to the hardware limitations, the acceleration control inputs are integrated into desired velocity inputs, where the velocity saturation limit is set to $|v_i| < 0.25m/s$. What's more, the steering controller presented in [10] is used for orientation control.

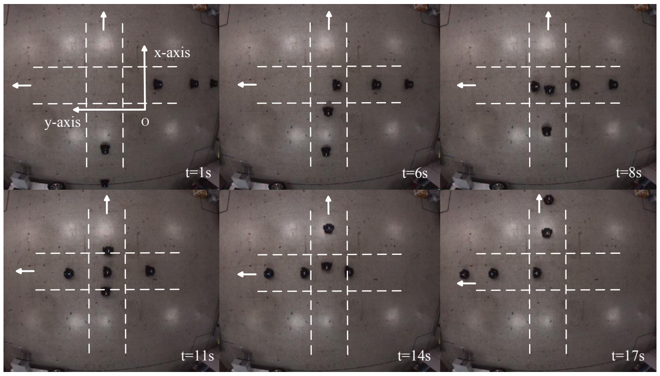

Fig. 6. Real scenarios in the non-stop intersection passing experiment.

In experiment 1, five vehicles are commanded to form a virtual platoon to pass the intersection without stoppings. The desired inter-vehicle distance between two virtual neighbors is set to $h_i^d = h^* = 0.36m$. The desired velocity of each vehicle is set to $v_i^d = v_r = 0.15m/s$, thus $\dot{v}_r = 0$. Then the proposed CACC controller can be transformed into the following form:

$$a_i = 5(v_r - v_i) + 10(h_i - h^*) + (v_{i-1} - v_i) - 10(h_{i+1} - h^*) - (v_i - v_{i+1}).$$

Once the vehicle has passed the intersection, the control strategy of the vehicle will be switched into keeping the desired velocity (and following the entity preceding vehicle, if exist).

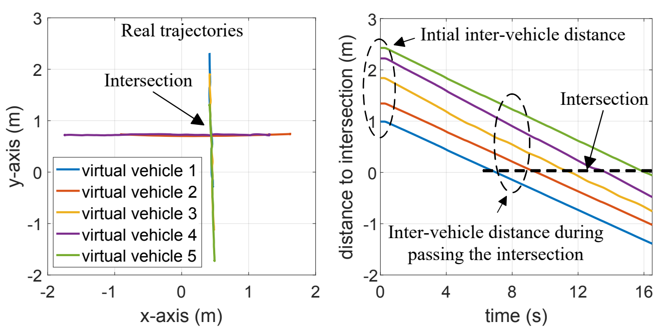

Fig. 7. Results of the non-stop intersection passing experiment.

Experiment results in Figure 6 and Figure 7 show that each vehicle can coordinate its motion with virtual neighbors and the inter-vehicle distance between each two neighboring vehicles converges to the desired value successfully, and the non-stop intersection passing purpose without vehicle collisions is achieved.

In experiment 2, the CACC task with four autonomous vehicles is considered, where the leader vehicle is commanded by a constant desired velocity $v_1 = 0.15m/s$ and $w_1 = 0.2rad/s$, and a constant desired inter-vehicle distance $h^* = 0.35m$ between each two neighboring vehicles is considered. The initial position of each following vehicle is placed randomly with large initial position errors and inter-vehicle distance errors.

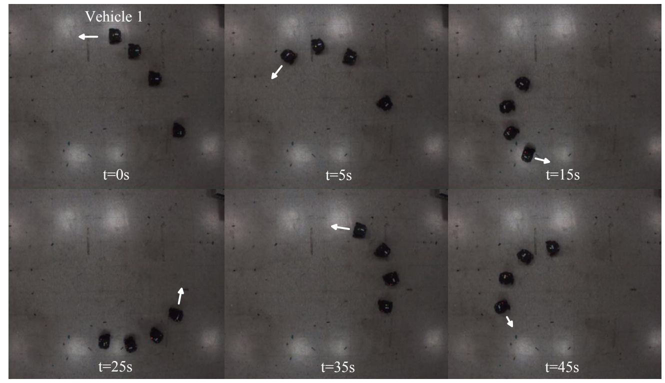

Fig. 8. Real scenarios in the CACC experiment.

Experiment results in Figure 8 and Figure 9 show that the inver-vehicle distance between each two neighboring vehicles converges to the desired value successfully, i.e., initial distance errors converge to zero simultaneously. Finally, each vehicle follows its preceding vehicle to track the desired circle trajectories and, in the meantime, keeps the desired inter-vehicle distances with the preceding and succeeding neighbors, thus the CACC task is accomplished.

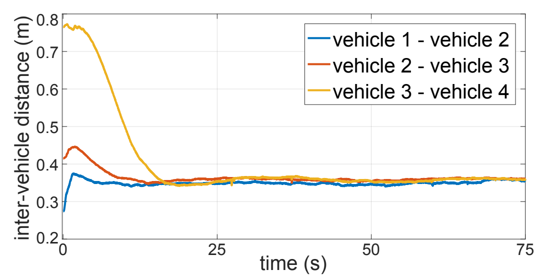

Fig. 9. Results of the CACC experiment.

VI. Conclusion

In this paper, a novel distributed CACC approach is first presented by utilizing the motion synchronization framework and based on which, a high-level intersection coordination system is further presented by introduce the spatial-temporal synchronization mechanism to achieve the robust CACC control based non-stop intersection passing. Lyapunov-based stability analysis is proposed to ensure the global convergence of the proposed control system. Simulation results validate the effectiveness and robustness of the proposed approach in the presence of substantial initial errors, acceleration saturation limits, external disturbances and communication delays. Finally, Real experiments in small-scale robotic systems demonstrate the practical applicability of the proposed approach.

In future work, we will take the practical vehicle dynamics into consideration, and test the proposed approach on real vehicle platforms.

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