Development of Optimal Cruise Control for Autonomous Vehicle

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***Abstract*—** **Cruise control is a servomechanism that controls the speed of motor vehicle automatically through external control setup. The control system takes over the throttle of the car to maintain steady speed as set by the driver. Connected cruise control (CCC) is an emerging technique which can significantly improve vehicle's connectivity, safety, and energy efficiency. V2V plays a major role in sharing large amount of reliable information among vehicles with unavoidable delays causing instability in the controller design. In this paper by an optimal control design is proposed for the CCC system by considering the presence of communication delays. Initially the dynamics of each vehicle in the platoon is modeled in detail, and then a linear quadratic optimization problem is formulated when the sampling period and communication delay are considered. An optimization problem is formulated with a quadratic cost function with the objective of minimizing state errors of vehicle as well as reducing energy consumption. By using backward recursion to realize vehicle close loop control under the influence of stochastic time delays with the optimal control strategy which is iteratively solved. The real-time control signals are determined online, and control gain can be calculated offline based on system states. The performance of the proposed algorithm is verified by numerical simulations at the end.**

Keywords—Connected cruise control, optimal control.

I. Introduction

Adaptive cruise control (ACC), advanced driver assistance systems (ADAS) can automatically control vehicle which is one of the widely used techniques in order to increase the safety and efficiency of the traffic flow. ACC system can avoid car accidents due to the fast sensing and actuating capabilities based on the reliable information captured by radar and other sensors. With development of wireless communication technology, vehicle-to-vehicle communication enriches the information sharing among vehicles. In order to achieve smaller inter-vehicle distance and better system reliability Cooperative adaptive cruise control (CACC) is one of the solutions integrating ACC and V2V communication[1]. However, the enhanced performance can only be achieved when all vehicles in the platoon are equipped with CACC systems, which may cause serious application limitations with heterogeneous vehicular platoon. Connected cruise control (CCC) realizes the joint design for the vehicle platoon to maintain smooth traffic flow which is an alternative to CACC. The CCC system provides a vehicle platoon with flexible connectivity structures and communication topologies. Each vehicle in the platoon can broadcast its available information to the CCC vehicle in order to achieve more accurate perception of the environments. The communication delay arises due to the imperfect wireless communication in the heterogeneous vehicular platoon[1].

In this paper, the optimal controller design for the CCC vehicle in a heterogeneous vehicular platoon with stochastic communication delays and the main contributions of this work are summarized as follows:

- A discrete-time vehicle platoon model is formulated with stochastic V2V communication delay, and an optimization problem is designed with a quadratic cost function.
- By using a backward recursion, the optimal control strategy is iteratively derived. The optimal control gain can be calculated 'Off-line', and the optimal control strategy is calculated 'On-line' in real time.
- The performance of the proposed algorithm is proved to be more stable than the existing algorithms by numerical simulations.

A. *Related work*

All the respective research work in done by referring to [1]. The research on CCC system has developed in wide range through different control strategies in recent years. The optimal control law for the CCC vehicle is proposed based on a continuous-time platoon model without delays. This study formulates the CCC problem as a linear quadratic tracking problem and optimal control algorithm is derived by directly solving the Riccati equation. The fast model predictive control (MPC)- based strategy is presented to ensure passenger comfort and fuel efficiency by the influence of the communication delay is omitted. The fixed input delay is considered in the controller design with a discrete- time-platoon model. By solving Lyapunov equation and the performance the optimal control algorithm is derived which is influenced by parameter initialization. The consensus-based algorithm is proposed in the presence of heterogeneous V2V communication delays and by taking uncertainties caused by time delays which is a distributed control strategy.

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II. Problem formulation and methodology

The problem is formulated with the CCC control problem considering vehicle's error dynamics and stochastic communication delays in the close-loop system. Fig. 1

indicates a typical platoon of 3 vehicles travelling on a single lane. Now consider the last vehicle is where CCC controller inserted and also receiving headway and velocity information through V2V communication from the vehicles ahead, The other vehicles are human-driven and are able to transmit information to the CCC vehicle. The first vehicle, seen as a tracking target which is running at determined velocity.

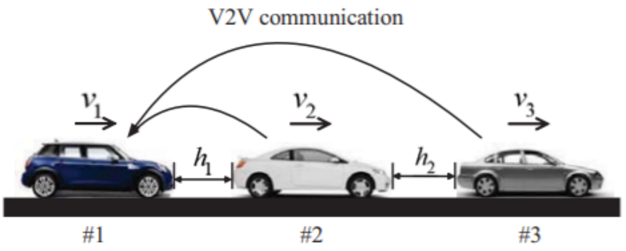

Fig. 1. The vehicular platoon structure.

In order to understand optimal control of the CCC vehicle, the dynamics equations of all vehicles in the platoon are formulated which is based on vehicle's headway and velocity information. The dynamics of the CCC vehicle is given as follows.

$$\dot{h}1(t) = v2(t) - v1(t), \quad (1)$$
$$\dot{v}1(t) = u(t - \tau)$$

where h1 is the headway distance between the CCC vehicle and its predecessor and v1 is the velocity of the CCC vehicle. x is the displacement and u(t) is the acceleration of the CCC vehicle which is the control signal. $\dot{h}1(t)$ and $\dot{v}1(t)$ denote the derivatives of h1(t) and v1(t) respectively. τ is the stochastic V2V communication delay.

For the other human-driven vehicles, the dynamics can be described as a car- following model bases on the human characteristic.

$$\dot{h}2(t) = v3(t) - v2(t), \quad (2)$$
$$\dot{v}2(t) = \alpha(V(h2(t)) - v2(t)) + \beta(v3(t) - v2(t))$$

Where α and β are the human driver parameters, h2 and v2 headway and velocity of the human driven vehicle in the platoon.

The objective for each vehicle in the platoon is to reach the desired headway h∗ and velocity v∗ = V (h∗). The state errors are defined as follows

$$s\,\tilde{h}(t) = h(t) - h*, \quad (3)$$
$$\tilde{v}(t) = v(t) - v*$$

From (1) and (3), the error dynamics of the CCC vehicle $\tilde{h}1(t)$, $\tilde{v}1(t)$ can be obtained. With the range policy: V (h) = V (h∗) + V (h∗)(h − h∗), and also based on the car-following model (2) and (3), the error dynamics of the human-driven vehicle $\tilde{h}i(t)$, $\tilde{v}i(t)$ can be obtained.

The state vector x = [$\tilde{h}1$, $\tilde{v}1$, $\tilde{h}2$, $\tilde{h}2$] T is determined by using the error dynamics of both CCC vehicle and human-driven vehicle, also the mathematical modal for the connected vehicular platoon can be formulated as

$$\dot{x}(t) = Ax(t) + Bu(t - \tau) \quad (4)$$

where the coefficient matrices are

$$A = [0\ -1\ 0\ 1;\ 0\ 0\ 0\ 0;\ 0\ 0\ 0\ -1;\ 0\ 0\ (\alpha f*)\ (-\alpha - \beta)]$$
$$B = [0;\ 1;\ 0;\ 0\ ]$$

Then, during the kth time period [kT, (k + 1)T], the discrete-time system can be derived as

$$x_{k+1} = A_k x_k + B_{k1} u_k + Bk_2 u_{k-1}$$

where,

$$A_k = e^{AT},\ x_k = x(kT),\ u_k = u(kT),$$
$$B_{k1} = \int_0^{T-\tau} e^{At}\, dtB,\ B_{k2} = \int_{T-\tau}^{T} e^{At} dtB$$

and T is the sampling period, τ_k is the stochastic time delay assumed to be smaller than T.

In this problem, the control objective is to regulate vehicle's longitudinal motion to reach the equilibrium $x^* \equiv 0$. In order to reduce energy consumption and realize smooth ride, the CCC vehicle's acceleration should also be considered. Therefore, the cost function is defined as a sum of the state errors and the control signals in a quadratic form as follows

$$J_N = \underbrace{E}_{\tau k}[x_N^T\, Qx N + \sum_{k=0}^{N-1}(x_k^T Q x_k + u_k^T R u_k)] \quad (5)$$

Where N is the finite time horizon, E(·) is the expectation operator, and the weight matrices are set as

$$Q = [1000;\ 0100;\ 0\ 0\ \varepsilon\ 0;\ 000\ \varepsilon]$$
$$R = 1$$

III. Optimal Controller Design

In this section, the optimal control strategy for the CCC vehicle is derived. We define a new state variable zk = [xT k uk−1] T , and then the discrete-time dynamic equation can change to

$$z_{k+1} = C_k z_k + D_k u_k$$
$$C_k = [A_k\ B_{k2};\ 0\ 0],\ D_k = [B_{k1}\ 1]$$

By using zk, the cost function in (6) is equivalent to

Where

$$\overline{Q} = [Q\ 0;\ 0\ 0]$$

Therefore, the optimal control problem is to minimize the cost function of the performance measure subjected to $\overline{Q}$

The optimal control strategy for CCC vehicle in according to minimizing the cost function of the system is given as

$$u_k = -L_k z_k,$$

where,

$$L_k = [P^T_k\, S_{k+1} P_k + R]^{-1}\, P^T_k\, S_{k+1} E_k, \quad (6)$$
$$S_k = E^T_k\, S_{k+1} E_k + \overline{Q} - L^T_k\, P^T_k\, S_{k+1} E_k \quad (7)$$

The residual cost function can be written as,

$$V_j = z_j^T\, S_j\, z_j \quad (8)$$
$$V_j = z^T_N\, \overline{Q} z_N + \sum_{k=j}^{N-1} z_k^T (\overline{Q} z_k + u_k^T\, R u_k) \quad (9)$$

(i)For j = N : The residual cost function V_N is the last term of the cost function J_N :

$$V_N = z_N^T S_N z_N \tag{10}$$

Where $S_N = \bar{Q}$.

(ii)For j = N-1: According to (9), the residual cost function V_{N-1} can be written as

$$V_{N-1} = z_N^T S_N z_N + (z_{N-1}^T Q z_{N-1} + u_{N-1}^T R u_{N-1}). \tag{11}$$

$$V_{N-1} = z^T_{N-1} [E^T_{N-1} S_N E_{N-1} + \bar{Q}] z_{N-1} + u^T_{N-1} P^T_{N-1} S_N E_{N-1} z_{N-1} + z^T_{N-1} E^T_{N-1} S_N P_{N-1} u_{N-1} + u^T_{N-1} [P^T_{N-1} S_N P_{N-1} + R] u_{N-1} \tag{12}$$

$$V_{N-1} = z^T_{N-1} H_{1,1} z_{N-1} + u^T_{N-1} H_{2,1} z_{N-1} + z^T_{N-1} H_{1,2} u_{N-1} + u^T_{N-1} H_{2,2} u_{N-1}$$

$$V_{N-1} = H_{2,2} (u_{N-1} + H_{2,2}^{-1} H_{2,1} z_{N-1})^2 + c \tag{13}$$

where c is totally determined by the system state z_{N-1}. In order to minimize the residual cost function in (20), the optimal control strategy u_{N-1} can be derived as

$$u_{N-1} = -L_{N-1} z_{N-1} \tag{14}$$

Where,

$$L_{N-1} = [P^T_{N-1} S_N P_{N-1} + R]^{-1} P^T_{N-1} S_N E_{N-1} \tag{15}$$

Obviously, when j = N − 1, the residual cost function can be written as a quadratic function of zN−1, which is determined by the current state x_{N-1} and the last control strategy u_{N-2}.

Obviously, at each sampling instant, the minimum residual cost function can be written in a quadratic form and the optimal control strategy is determined by the system states. From the derivation above, we observe that the optimal control gain Lj can be iteratively derived based on (12), and the optimal control strategy uj is a linear function of zj.

IV. Algorithm for Optimal Cruise Control

//RELATION BETWEEN POSITION & VELOCITY(MATLAB)

#OPTIMAL_CRUISE_CONTROL.m
Setup - Initial conditions **[A,B,Ak,Bk1,Bk2] ← [ ]**
Weighting and Dynamic Steady State Constants
[E,P,U,O] ← [ ]
Discretize E,P
Check for Controllability **control = ctrb(E,P)**
Q and S initial Values **[Q,S] ← [ ]**
Iterative Process
for K ← N-1:-1:1
do
Riccati Recurrence
u(K) ← -L(K,:)*X(:,K);
L(:,K+1) ← E*X(:,K) + P*L(K,:)*X(:,K);
End - Iterative Process
Plot Result

V. Simulation and Results

In this section, numerical simulations are provided to verify the performance of the proposed control algorithm. As a case study, the vehicular platoon for headway is illustrated in Fig. 1 is considered. Three vehicles are running on a single lane, more specifically, the tail vehicle is the CCC vehicle, the vehicle in the middle and the leading vehicle are human-driven vehicles.

The system parameters are set as α = 0.6, β = 0.6, vmax = 30[m/s], hmin = 5[m], hmax = 35[m], and the initial and desired states are set to be h(0) = 10[m], v(0) = 8[m/s], h∗ = 20[m], v∗ = 15[m/s]. The leading vehicle is running at the desired velocity all the way and other vehicles in the platoon start with the initial states. In the simulations, various values of the sampling period T are chosen to verify the performance of the proposed algorithm. We set the communication delay as τ = 0.15s. The results are shown in Fig. 2, Fig. 3, and Fig. 4. It is obvious that the CCC vehicle's velocity and headway gradually reach the desired states, and the control signal u, namely the CCC vehicle's acceleration, converges to almost zero. Thus, the proposed optimal control algorithm can regulate vehicle's longitudinal motion in all cases.

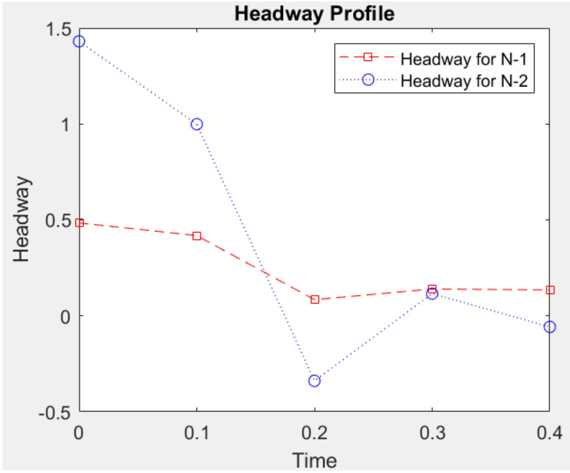

Fig. 1. Headway of the CCC vehicle with various sampling periods and time delays using the proposed algorithm.

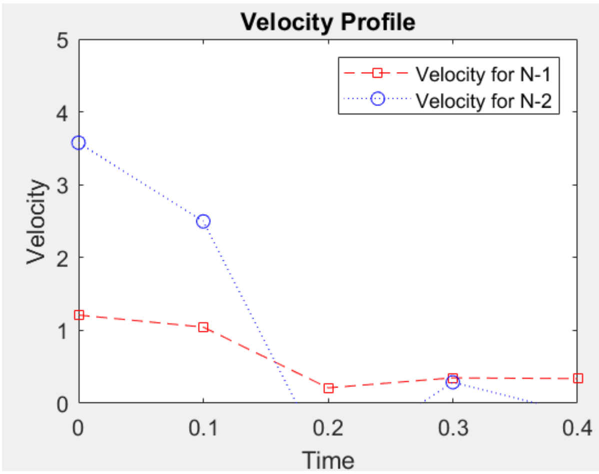

Fig. 2. Velocity of the CCC vehicle with various sampling periods and time delays using the proposed algorithm.

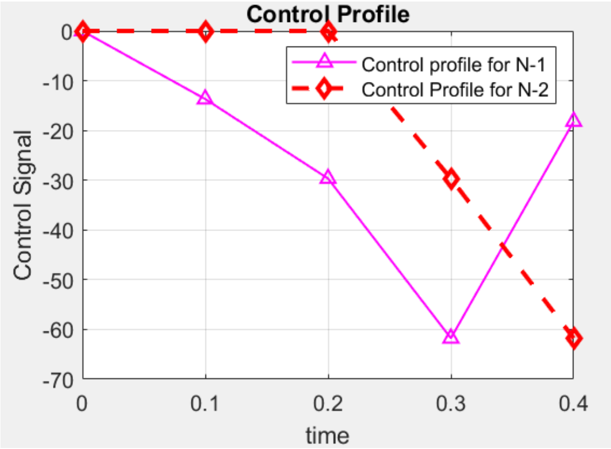

Fig. 3. Control signal of the CCC vehicle with various sampling periods and time delays using the proposed algorithm.

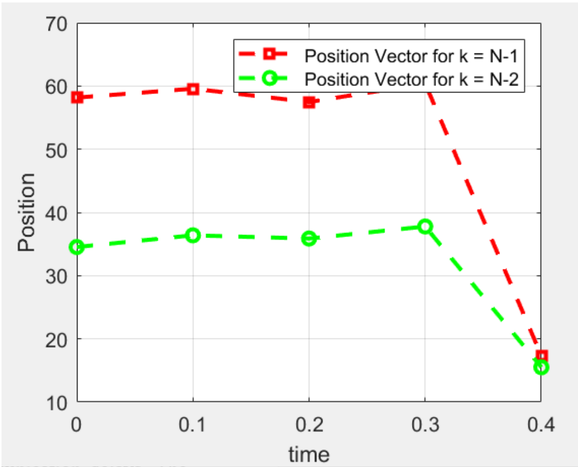

Fig. 4. Position of the CCC vehicle with various sampling periods and time delays using the proposed algorithm.

VI. Conclusion

In this paper, we analyze the connected cruise control problem considering the V2V communication delays. The system is modeled as a discrete-time system which have the capability of communicating, computing, coaching and control. Finally a linear quadratic optimal control problem is formulated in order to minimize the deviations of the CCC vehicle's headway and velocity. The optimal control strategy can be iteratively solved using the recursion.

VII. References

[1] Zhuwei Wang, Yu Gao and Chao Fang 'Optimal Control Design for Connected Cruise Control with Edge Computing, Caching, and Control'

[2] Donald E. kirk reference book 'Optimal Control Theory'