Adaptive Cruise Control: A Model Reference Adaptive Control Approach

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***Abstract*—This paper presents a Model Reference Adaptive Control (MRAC) based framework for vehicle adaptive cruise control systems. The linear longitudinal dynamic model is created with uncertainties in the state and input matrix. The controller structure aims to handle these uncertainties and also maintains the desired distance with the lead vehicle. To evaluate the performance of the proposed controller, several simulation studies are conducted by comparing the results with a linear state feedback controller via MATLAB/Simulink. Whereas the linear controller underperforms under uncertain conditions, it is seen that MRAC achieves the desired performance despite model uncertainties.**

***Index Terms*—Adaptive Cruise Control, Model Reference Adaptive Control, Longitudinal control, Vehicle dynamics**

I. Introduction

In recent years, the increasing demand for vehicles has brought additional burden on current traffic infrastructure. To deal with this problem, Advanced Driver-Assistance Systems (ADAS) and autonomous driving applications have been an active research area, both in institutes and automotive companies [1]. Today's vehicles are deploying many ADAS systems like Adaptive Cruise Control (ACC), Emergency Brake Assist (EBA), Active Lane Assist and Lane Keeping Assist (LKA) to passenger vehicles to provide comfort and ensure safety. ACC which is an extension of traditional Cruise Control (CC), has been one of the promising technology with the advent of advanced perception and control systems. In an ACC system, the ego vehicle follows the leading vehicle without interaction of the driver by maintaining a safe distance. A step ahead of ACC would lead to Cooperative Adaptive Cruise Control (CACC), which also utilizes the Vehicle-to-Vehicle (V2V) communication, to prevent collision and increase traffic flow compared to ACC [2]. Today's ACC systems mainly focus on tracking a desired distance from a predecessor vehicle or tracking a desired speed. ACC system has additional advantages, such as fuel economy and driver desired response [3]. Despite its many benefits, the design of an ACC system for multiple objectives becomes a challenging problem particularly when the system model contains uncertainty.

A review of the recent literature shows that designing an ACC system has been investigated in many aspects. A Nonlinear Model Predictive Controller (NMPC) is proposed in [4], a switching strategy that depends on the controlled vehicles environment was developed. Also, [5] extensively analyzed the design of CC and ACC systems. The nonlinear model of the equation of motion for longitudinal vehicle dynamics is linearized, then PI/PID based CC/ACC structures are implemented in detail. The authors in [6] designed a string-stable CACC system, with a time-headway of less than 1s. In addition to this study, in [7], a new CACC structure is offered to overcome the homogeneity assumption as well as handle the inevitable communication losses. An adaptive switched control strategy that is based on MRAC activates a CACC or an ACC depending on communication reliability. A nonlinear ACC structure based on the sliding mode technique which included a nonlinear range policy is designed for improved traffic flow stability and string stability in [8]. In [9], a simplified approach for energy-efficient ACC based on MPC is proposed. MPC based method is used to minimize energy consumption. An experimental study with a test vehicle is conducted in [10] to design a fuel-efficient predictive ACC structure. For this purpose, a prediction model of the leader vehicle is introduced and an MPC algorithm is implemented to obtain the optimal desired acceleration of the following vehicle.

In addition to these studies, several methods are also proposed to handle the uncertainties in model and controller structure. In [11], a feedback linearization approach is applied to design an ACC System that deals with system non-linearities. An on-road test is conducted to show the effectiveness of the approach. An intelligent PI controller was proposed in [12] to design an ACC system. The approach uses a "traditional PI controller" and a feed-forward term that eliminates error due to model uncertainties.

In [14], an Adaptive Optimal Control approach was proposed for a heterogenous CACC system with uncertain dynamics. Therein, the authors developed a model based on system error. The proposed method computes an adaptive optimal feedback gain iteratively from the famous Algebraic Ricatti Equation (ARE). In this paper, a Model Reference Adaptive Controller (MRAC) is applied to design a spacing controller for an ACC system with uncertainties in low-level dynamics. The controller gains are computed using the MRAC scheme. The system is designed based on error dynamics. Lead vehicle velocity is treated as an exogenous disturbance. Practical implementaion of the proposed framework is easy, because

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only a sensor that measures the controlled vehicle speed, relative distance between the lead and controlled vehilcle is necessary.

The remainder of this paper is organized as follows. In Section II, the objective of ACC problem is given in detail. The proposed MRAC control approach is formulated in Section III. Extensive simulation-based analysis is conducted and the results are discussed in Section IV. In the last Section, concluding remarks are presented.

II. Problem Statement

To design the ACC system, an interactive model of the controlled and lead vehicle is created. The basic representation of an ACC system is shown in Fig. 1. By adjusting the speed of the controlled vehicle, a desired distance is maintained with the lead vehicle. The change in the lead vehicle speed acts as an exogenous disturbance to the overall system. The longitudinal dynamics of the controlled vehicle is nonlinear, due to the nonlinearity of engine torque maps, time-varying gear position, as well as drag force. However, a linear first-order model which is given in (1) may be obtained with the help of the feedback linearization method to represent the overall dynamics.

$$\tau \dot{x}_1(t) = -x_1(t) + u(t) \tag{1}$$

where, x_1 is the controlled vehicle velocity, τ is the actuator delay, u is the desired velocity. The distance between vehicles is measured by a radar sensor which is mounted on the controlled vehicle front bump. So, the derivative of relative distance between vehicles may be modelled by using the velocities of vehicles as given in (2).

$$\dot{x}_2(t) = v_l(t) - x_1(t) \tag{2}$$

where, x_2 is the relative distance between vehicles and v_l is the velocity of the leading vehicle. The constant time headway policy given in (3), is utilized to define the desired distance between vehicles.

$$y_r(t) = d_0 + t_h x_1(t) \tag{3}$$

where, y_r is the desired relative distance, d_0 is the standstill distance and t_h is the time headway. Then, if the relative distance between vehicles is represented with $y = x_2$, the controller problem turns to find a control signal u which provides the following objectives.

$$\lim_{t\to\infty} ||y(t) - y_r(t)|| = 0 \tag{4}$$

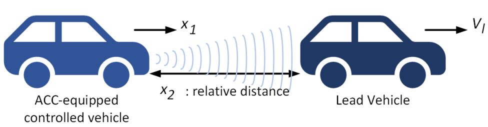

Fig. 1. Adaptive Cruise Control (ACC) system representation

III. Controller Design

A. Closed-Loop System Model

The ACC system keeps the relative distance between vehicles at the desired value by driving the error signal to zero. To achieve this objective, the state equation of the overall system is created by adding the integral of the error ($\int(y - y_r)$) to the system as given in (5). Here, to reduce the complexity of notation, t which represents the time is omitted.

$$\begin{bmatrix}\dot{e}_1\\ \dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 0 & 1\\ 0 & -\frac{1}{\tau} & 0\\ 0 & -1 & 0\end{bmatrix}\begin{bmatrix}e_1\\ x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0\\ 1\\ 0\end{bmatrix}\frac{u}{\tau} + \begin{bmatrix}-1\\ 0\\ 0\end{bmatrix} y_r + \begin{bmatrix}0\\ 0\\ v_l\end{bmatrix} \tag{5}$$

To make a simple representation, (5) can also be rearranged as follows by adding the output equation;

$$\begin{aligned}\dot{x} &= Ax + B\Lambda u + B_{ref} y_r + \omega\\ y &= x_2\end{aligned} \tag{6}$$

where, A is the system uncertain matrix, B is the input vector, Λ is the uncertain input which is defined as $\Lambda = \frac{1}{\tau}$, B_{ref} and ω are self-evident from (5). It should be stated that the lead velocity is treated as an exogenous disturbance.

B. Model Reference Adaptive Controller Design

MRAC is a nonlinear control algorithm that forces a system to track a predetermined model [13]. Here, τ represents the inertial time delay of the system whose value depends on the low-level dynamics of the vehicle as given in [14]. Performance of ACC (or CACC) system can degrade as the value of τ varies from the nominal value. MRAC is designed to achieve desired performance despite uncertainty in τ. This is done by updating control parameters online, based on deviation of the measured states from their desired values. The idea is to use the nominal (estimated) τ to design the reference model and use MRAC to track the reference model in case of uncertainty.

The reference model is defined as follows;

$$\begin{aligned}\dot{x}_{ref} &= A_{ref} x_{ref} + B_{ref} y_r\\ y_{ref} &= x_{2,ref}\end{aligned} \tag{7}$$

where, x_{ref} is the reference state vector, A_{ref} is known and Hurwitz, B_{ref} is known and y_r is the reference input, y_{ref} is the reference output.

Assume that, there exist $\hat{K}^T$ such that $A_{ref} = A + B\Lambda\hat{K}^T$ ($\hat{K}^T$ can be computed using pole-placement technique, LQR method, etc). Hence,

$$\dot{x} = A_{ref}x + B\Lambda(u - \hat{K}^T x) + B_{ref} y_r + \omega \tag{8}$$

The control input is basically chosen as $u = K^T x$, where K^T is the adaptive gain. Substituting u in (8) results in;

$$\begin{aligned}\dot{x} &= A_{ref}x + B\Lambda(K^T x - \hat{K}^T x) + B_{ref} y_r + \omega\\ &= A_{ref}x + B\Lambda(\Delta K^T)x + B_{ref} y_r + \omega\end{aligned} \tag{9}$$

Define the state tracking error as $e = x - x_{ref}$, where $\dot{e} = \dot{x} - \dot{x}_{ref}$, from (7) and (9)

$$\dot{e} = A_{ref} e + B\Lambda(\Delta K^T)x + \omega \tag{10}$$

The theorem given below simply describes the results of model reference adaptive controller.

Theorem. Given a Lyapunov candidate of the form $V(e, \Delta K) = e^T Pe + tr(\Delta K^T \Gamma^{-1} \Delta K \Lambda)$ with update law $\dot{K} = -\Gamma x e^T PB, \dot{V}(e, \Delta K) \leq 0$; where $\Gamma > 0$ is the adaptation rate and $P > 0$ is the unique symmetric positive-definite solution of the algebraic Lyapunov equation below, with $Q = Q^T > 0$.

$$PA_{ref} + A_{ref}^T P = -Q \tag{11}$$

Proof. See [15] for the proof.

Hence, $\lim_{t\to\infty} e(t) = 0$, where $e(t) = x(t) - x_{ref}(t)$. Since $y = x_2$ and $y_{ref} = x_{2,ref}$, the system output asymptotically tracks the reference model output y_{ref}. Also, since the reference model is chosen to track any external bounded reference input y_r, with bounded errors, the output will also track y_r.

The algorithm steps of MRAC is given below;

1) Compute x_{ref} from the pre-determined reference model (7).
2) Obtain x from system model (uncertain model) (6)
3) Compute the error state error by using $e = x - x_{ref}$
4) Calculate $\hat{K}^T$, such that $A_{ref} = A + B\Lambda\hat{K}^T$ is Hurwitz (pole placement, LQR, etc.).
5) Solve (11) for $P > 0$ with $Q = Q^T > 0$
6) Define the adaptation rate Γ.
7) Define the adaptive law (update law) $\dot{K} = -\Gamma x e^T PB$
8) Find control input $u = K^T x$ (go to step 1)

IV. Numerical Simulations

In this section, a numerical simulation example is provided to show the effectiveness of the proposed controller structure. The simulations are carried out with MATLAB/Simulink for ACC follow mode and ACC stop-and-go modes.

A. ACC Follow Mode

For this scenario, ACC follow mode is activated when the controlled vehicle detects a vehicle in the driving line with the radar sensor. The simulation parameters are given in Tab. I. For this case, the performance of the proposed controller is evaluated with a constant actuator delay (τ).

TABLE I
Parameters of simulation example

Description	Value	Unit
Velocity of leading vehicle (v_l)	60 (16.67)	[km/h] ([m/s])
Initial position of leading vehicle (d_0)	5	[m]
Initial position of controlled vehicle	0	[m]
Time headway (t_h)	2	[m/s]
Actuator delay (τ)	0.5	[s]

The reference model is designed by the help of LQR technique with $Q_{lqr} = diag(\begin{bmatrix}10 & 0 & 0\end{bmatrix})$ and $R = 1$. $\hat{K}^T$ is calculated as $\hat{K}^T = \begin{bmatrix}3.1623 & -1.1688 & 3.7036\end{bmatrix}$, therefore A_{ref} is obtained as follows;

$$A_{ref} = A + B\Gamma\hat{K}^T = \begin{bmatrix} 0 & 0 & 1 \\ 6.3246 & -4.3376 & 7.4072 \\ 0 & -1 & 0 \end{bmatrix}$$

After tuning, the control parameters are selected as;

$$P = \begin{bmatrix} 11.2838 & -0.3953 & 7.2862 \\ -0.3953 & 0.881 & -1.3212 \\ 7.2862 & -1.3212 & 11.8608 \end{bmatrix}, \Gamma = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 20 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

In Fig. 2 velocities of the leading and controlled vehicles are shown and in Fig. 3 and 4, the relative distance and relative distance error are given, respectively. The results show that MRAC performs satisfactory. In the steady state, the controlled vehicle tracks the lead vehicle with a relative distance error of less than 0.005 m.

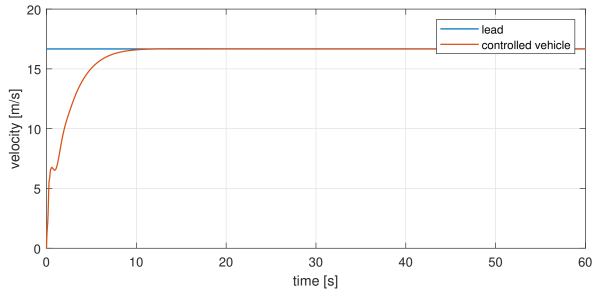

Fig. 2. ACC follow mode - constant speed tracking

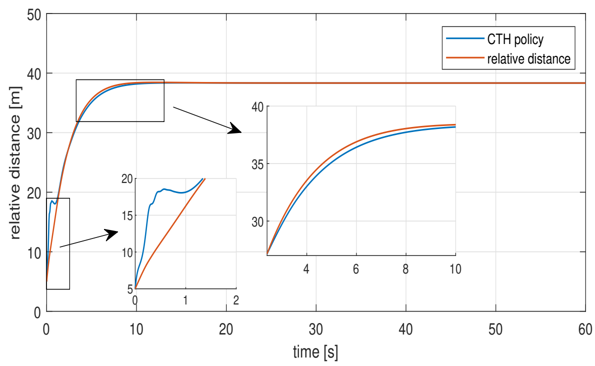

Fig. 3. ACC follow mode - relative distance

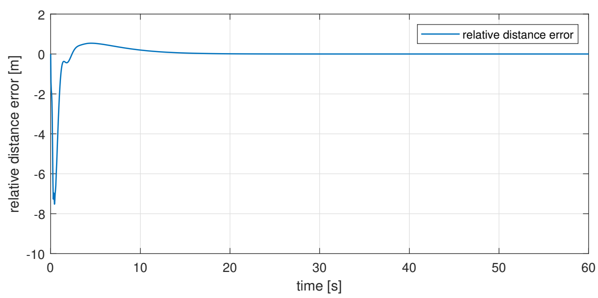

Fig. 4. ACC follow mode - relative distance error

B. ACC Stop-and-Go Mode

The second scenario considers the performance of the controller under a stop-and-go mode which can lead to reduced traffic jam. In this case, the lead vehicle initially moves with a constant speed of 60 km/h and then increases its speed gradually along away. At 60 s, the lead vehicle suddenly stops for 20 s and starts moving with a speed of 30 km/h. Fig. 5, 6 and 7 demonstrate the performance of the MRAC with no uncertainty in the system (τ is constant).

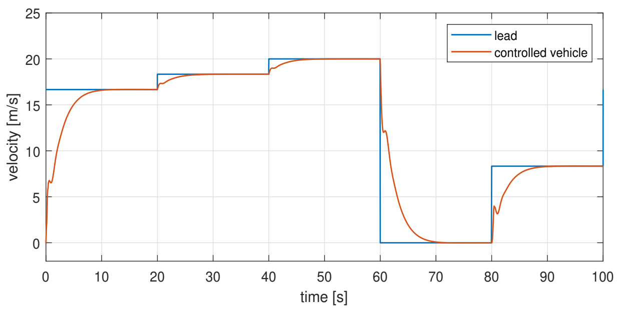

Fig. 5. ACC stop-and go mode - Speed tracking

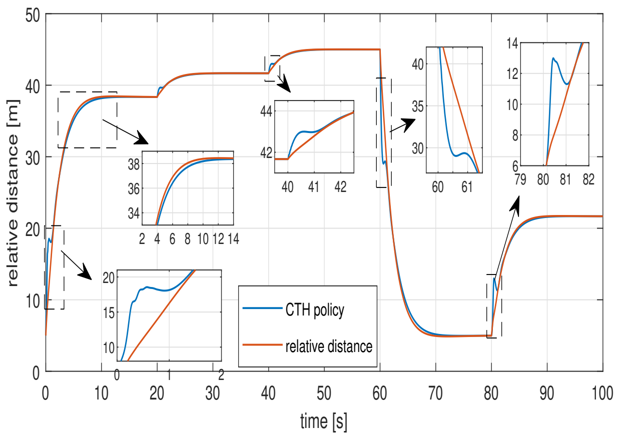

Fig. 6. ACC stop-and-go mode - Relative distances

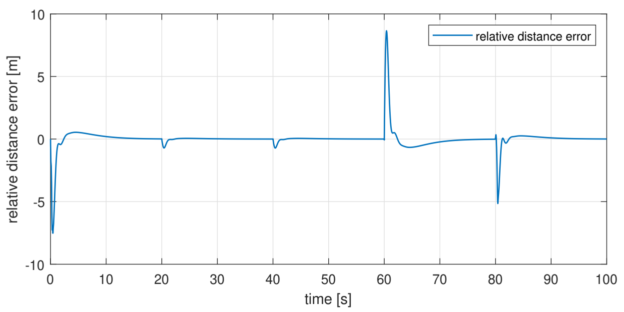

Fig. 7. ACC stop-and-go mode - Relative distance error

It is concluded that controlled vehicle track the lead vehicle in a proper way. When the lead vehicle stopped, the controlled vehicle maintained the relative stop distance ($d_0 = 5m$) for this case). And when the lead vehicle began to move (at $80s$), the controlled vehicle continued to maintain the safe relative distance.

For the final case, the effectiveness of the proposed controller is validated in the presence of parametric uncertainty which is the actuator delay shown in Eq (6). The performance of the MRAC is compared with a nominal state feedback controller which is calculated as $\hat{K^T} = \begin{bmatrix} 3.1623 & -1.1688 & 3.7036 \end{bmatrix}$. Initially, the actuator delay τ is set to its nominal value $\tau = 0.5s$, then it is increased to $\tau = 1.5s$ and finally $\tau = 4s$. Fig. 8, 9 and 10 show the speed tracking performance of the two controllers.

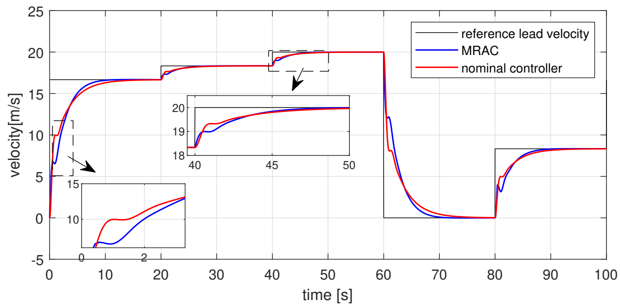

Fig. 8. ACC stop-and-go mode - Speed tracking ($\tau = 0.5s$)

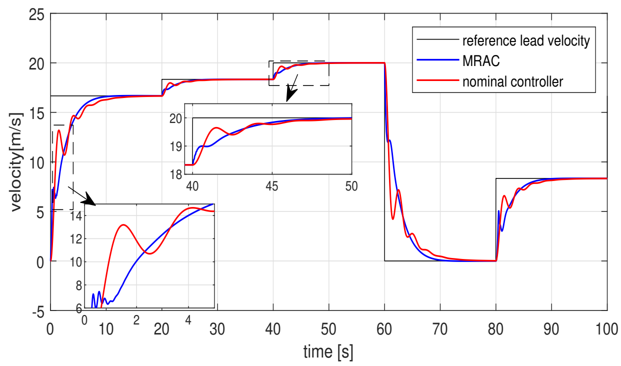

Fig. 9. ACC stop-and-go mode - Speed tracking ($\tau = 1.5s$)

It is concluded that the performance of MRAC is better than nominal feedback controller for all uncertain scenarios. When the uncertain parameter increases, the performance of the nominal controller deteriorates and even leads to oscillation (especially during the stop duration, $(60 - 80s)$), however MRAC still displays satisfactory performance.

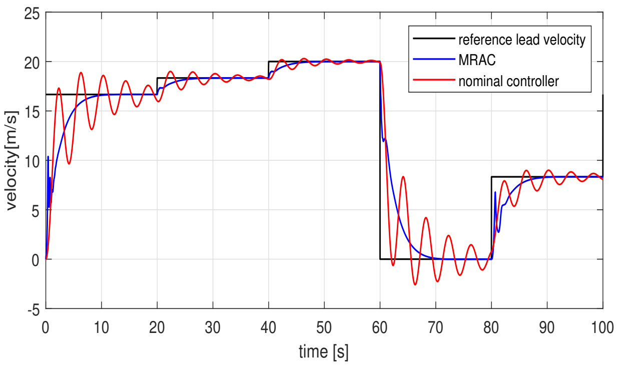

Fig. 10. ACC stop-and-go mode - Speed tracking ($\tau = 4s$)

Conclusion

In this paper, a Model Reference Adaptive Control (MRAC) has been applied to design an ACC system. Simulation results were presented. The ability of MRAC to perform despite uncertainties has been demonstrated. The structure of the controller is suitable for real-time implementation. The controller is a good candidate for practical implementation, in addition to the vehicle velocity, only a sensor that measures relative distance is needed for practical implementation.

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