



Development of a Model Reference Adaptive Controller for String Stability in Truck Platooning

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ABSTRACT

This research developed a model reference adaptive controller for string stability in truck platooning. String stability is the ability of a platoon to maintain a stable formation as disturbances propagate through the string of vehicles resulting in oscillations or collisions. These disturbances include vehicle breakdown, intruding vehicles, change in speed or position. Designing an adaptive platoon controller that adapt to the disturbances and varying working conditions (such as road conditions and driving behaviours) while ensuring safety, stability, and efficiency has been explored in literature. This leads to the development of adaptive Proportional Integral Derivative (PID) Controller, Model Predictive Controller (MPC), sliding mode controller (SMC), and H-infinity (H_{∞}) controller for string stability of a platoon. However, the performance of these control schemes is affected by the model complexity and parameter uncertainty of the system resulting to an unstable system. In order to address these problems, a reference model of the trucks and adaptive mechanism is designed for error estimation and controller parameter adjustments respectively. A stabilizing controller was designed based on the concept of Lyapunov energy function. The performance of the controller is evaluated by comparing with that of MPC incorporated with PID controller using vehicle distance, vehicle velocity, inter vehicle gap error and velocity error as performance metrics. The simulation results obtained shows that MRAC has a better tracking performance and updates the controller in real-time there by attenuates disturbance when compared to DMPC- PID with an improvement in achieving a constant intervehicle gap of 20 m, a desired speed of 20 m/s at a settling time of 20 seconds. The simulation result shows a reduction in average intervehicle gap error of 0.15 m from the leader vehicle to the follower vehicles. An average velocity error of 0.13 m/s between the leader vehicle and followers. It also recorded an average acceleration of 0.73 m/s² and deceleration of 0.27 m/s² to achieve the desired steady state speed. The designed controller shows improvements over the existing control technique in terms of the intervehicle gap and system stability in the platoon.

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INTRODUCTION

The demand for highway travel keeps on growing as the population rises, especially in

urban areas. The capacity of goods transportation alone has been projected almost double by 2020, hence intelligent transportation with a feasible

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control algorithm is important to ensure smooth traffic flow on the highway (Musa *et al.*, 2018). The field of intelligent transportation system (ITS) has grown significantly due to advancement in wireless communication, data processing control system, artificial intelligent algorithms, machine learning, adaptive cruise control, among others, which enable vehicle to navigate at a cruise speed that adapts to the speed of preceding vehicle (Villenas *et al.*, 2023).

Vehicle platooning is a group of vehicles travelling in a closely coordinated convoy communicating electronically with each other, in which one vehicle following another at a close distance. The prospect of road transport has improved with the promises offered by autonomous vehicle as a means for future navigation, increased safety, reduced CO₂ emission and avoid traffic accident caused by drivers' fatigue (Ajayi *et al.*, 2022). The truck platoon control is composed of the lateral control and the longitudinal control. The lateral control is to keep a following truck behind its predecessor truck while longitudinal control of the truck is responsible for regulating the vehicle cruise speed and desired position (Feng *et al.*, 2023).

PROBLEM STATEMENT

Truck platooning serves as a practical application and testing ground for emerging technologies such as vehicle-to-vehicle communication, automated driving features and artificial intelligence algorithms by gradually introducing and refining these technologies in real world scenarios. String stability is the property that disturbances are attenuated as they propagate along the stability of interconnected vehicles that guarantee uniform boundedness of all the states of interconnected vehicles for all time in the platooning. The implementation of autonomous driving in real life is mainly affected by the string stability in the platoon. The control design of this research is aimed at addressing the limitation of the existing control algorithms by guaranteeing collision safety at all times and attenuating disturbances along the platoon methodology

Development of a Vehicle Model

The vehicle model is based on the fact that. The vehicle model was formulated from Newton third law of motion that say's tractive force is equal to resistive force;

$$F_{tr} = F_a + F_i + F_g + F_r \quad (1)$$

Where the respective forces are defined as:

$$\left. \begin{aligned} F_a &= \frac{1}{2} \rho C_d A v^2 \\ F_i &= ma \\ F_r &= mgC_{rr} \\ F_g &= mgsin\theta \end{aligned} \right\} \quad (2)$$

Where; aerodynamic drag force (F_a), rolling resistance force (F_r), gradient force (F_g), inertia force and tractive force (F_{tr}), ρ is the air density, v is the velocity, C_d is the drag coefficient, A is the frontal area, m is the mass, and a is the acceleration.

Let

$$\left. \begin{aligned} x_1 &= s \\ x_2 &= v \\ \dot{x}_1 &= v \\ \dot{x}_2 &= a \end{aligned} \right\} \quad (3)$$

From equation (1)

$$\left. \begin{aligned} F_{tr} &= \frac{1}{2} \rho C_d A v^2 + mgC_{rr} + mgsin\theta + ma \\ ma &= F_{tr} - \frac{1}{2} \rho C_d A v^2 - mgC_{rr} - mgsin\theta \\ \dot{x}_2 &= \frac{F_{tr} - \frac{1}{2} \rho C_d A v^2 - mgC_{rr} - mgsin\theta}{m} \end{aligned} \right\} \quad (4)$$

The acceleration of vehicle \dot{x}_2 , is defined in the state equation as obtained from equation (4).

Designing the Reference Model

The reference model \dot{X}_m of a vehicle in MRAC design is in the form of

$$\dot{X}_m = (A - BK_1)X_m + BK_2r \quad (5)$$

With; $A_m = A - BK_2$ and $B_m = BK_2$

Where A_m and B_m stands for constant plant parameter, r is the reference signal, K_1 and K_2 represent the adaptive gains and X_m is the

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system state vector. The vehicle dynamic model (plant model) is defined from equation (3.4) as;

$$\dot{x}_2 = -g \sin \theta - \frac{1}{2m} \rho C_d A v^2 + \frac{1}{m} F_{tr} \quad (6)$$

The derivative of the state of the reference model of the vehicle is obtained by neglecting the effect of rolling friction (F_r):

$$\left. \begin{aligned} \dot{x}_1 &= v = x_2 \\ \dot{x}_2 &= -g x_1 - \frac{1}{2m} \rho C_d A x_2^2 + \frac{1}{m} F_{tr} \end{aligned} \right\} (7)$$

Where $\sin \theta \approx \theta = x_1$. The state equation model of the vehicle is written in the form of $\dot{X} = AX + Bu$ as:

$$\dot{X} = \dot{x}_2 = \begin{bmatrix} 0 & 1 \\ \frac{1}{2m} \rho C_d A x_2^2 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} F_{tr} \quad (8)$$

The reference state model is obtained by neglecting road grade ($\theta \approx 0$) since the vehicle operates in a flat road therefore written as:

$$\dot{X} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} X + \frac{1}{m} \begin{bmatrix} 0 \\ 1 \end{bmatrix} F_{tr} \quad (9)$$

Where the system plant parameter $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$

and $B = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}$

The reference vehicle model is derived by its characteristic polynomial, which dictates the desired closed-loop dynamics of the system. The characteristic polynomial of a second-order system;

$$P(s) = s^2 + 2\xi s + \omega^2 \quad (10)$$

The state space model of the vehicle is obtained;

$$A_m = \begin{bmatrix} 0 & 1 \\ \omega^2 & 2\xi\omega \end{bmatrix} \text{ and } B_m = \begin{bmatrix} 0 \\ \omega^2 \end{bmatrix}$$

Then the reference model of the system is achieved by substituting the state space vectors in equation (4) where A_m is

$$\dot{X}_m = A_m X_m + B_m K_2 \quad (11)$$

Formation of Optimization Problems

The goal is to minimize the ISE with respect to the controller parameters (K_1 and K_2). The objective function can be written as:

$$J(K_1, K_2) = \int_0^t e(t)^2 dt \quad (12)$$

Where $e(t)$ depends on the system dynamics and the control law defined by K_1 and K_2 . The optimization problem for the control parameters (K_1 and K_2) tuning can be formulated as:

$$\min_{K_1, K_2} J(K_1, K_2) = \int_0^t (X - X_m)^2 dt \quad (13)$$

Subjects to:

$$\begin{aligned} K_1, K_2 &> 0 \\ K_2 &> K_1 \end{aligned}$$

RESULTS

Control gain

Figure 1 shows the plots of MRAC that achieved a better controller performance with the control gains $\gamma_1 = 0.01$ and $\gamma_2 = 1.40$.

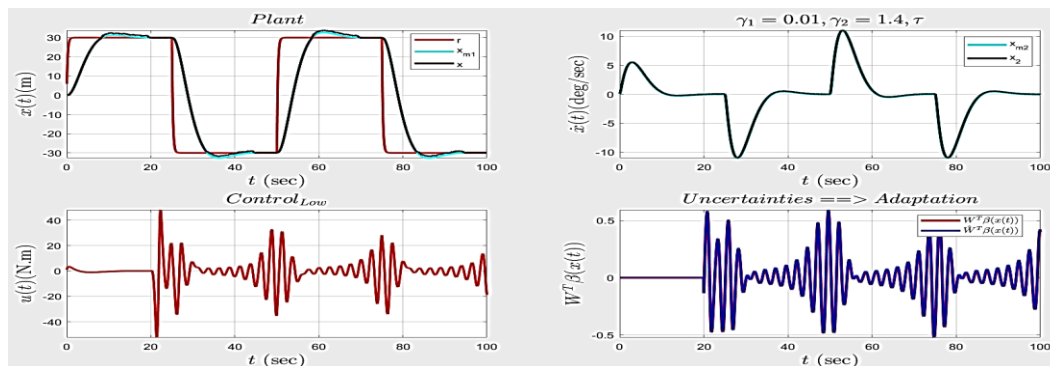


Figure 1: MRAC control gain $\gamma_1 = 0.01$ and $\gamma_2 = 1.40$

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From the controller performance presented in Figure 4.3, it can be seen that there is an improved performance in the adaptive law to track a reference trajectory under uncertainty and external disturbance. In general, the controller performance clearly indicates that the actual velocity aligns with the reference velocity, demonstrating MRAC ability to manage model uncertainty effectively even in the presence of small oscillation along the platoon.

Velocity Profile of the Trucks

Figure 2 shows the plots for the velocity profile of the four trucks in the platoon with all the trucks showing discrepancy in terms of initial velocity.

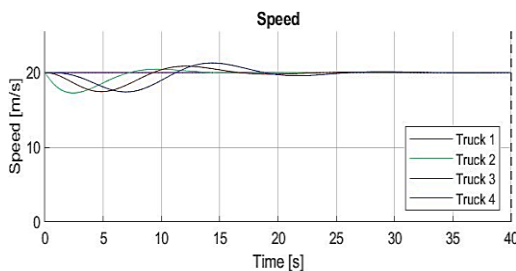


Figure 2: Velocity Profile of the Trucks

From Figure 2, it can be seen that the trucks attain a steady state speed of 20 m/s at a settling time of approximately 20 seconds, which indicates that the MRAC controller effectively synchronizes the speed of the trucks as they travel cohesively along the platoon.

Acceleration Profile of the Truck

Figure 3 shows the plots for the acceleration profile of the four trucks in a platoon which exhibits some variation in their acceleration.

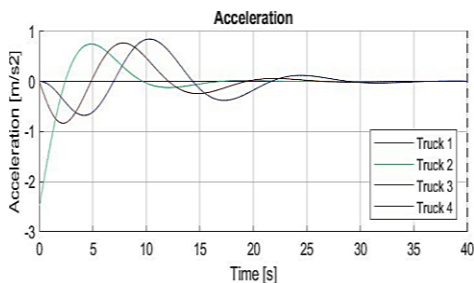


Figure 3: Acceleration Profile of Four Trucks

From Figure 3, it is observed that Truck 2 decelerates for a duration of 3 seconds due to its initial inter-vehicular distance of 10 m from Truck 1, which is below the desired spacing of 20 m. This deceleration ensures that the desired inter-vehicular distance is achieved. A similar adjustment is observed for Trucks 3 and 4, although at a lower rate of deceleration.

After 20 seconds, the acceleration of all trucks reaches a steady state of zero, indicating that the trucks are moving at a uniform velocity with the desired spacing maintained throughout the platoon. The MRAC effectively mitigates the initial variations, ensuring that the trucks' accelerations converge to stable values. This showcases the adaptability and robustness of the adaptive control law in handling dynamic conditions while maintaining platoon stability.

CONCLUSION

The Model Reference Adaptive Controller (MRAC) is an advanced adaptive control strategy designed to compute the control input of a system such that its output closely matches that of a predefined reference model. MRAC employs an adaptive optimization algorithm to adjust controller parameters in real time, ensuring robust performance in the presence of system uncertainties and external disturbances.

To address model uncertainties affecting system stability, maintain constant inter-vehicle spacing, and achieve the desired speed within a truck platoon, an MRAC was developed using optimal control gains and an adaptive mechanism. The controller design and simulations were implemented in MATLAB 2023b, and its performance was evaluated using standard performance metrics.

The simulation results obtained show that MRAC has a better tracking performance and updates the controller there by attenuating disturbance when compared to DMPC-PID with an improvement achieving a constant intervehicle gap of 20 m, a desired speed of 20 m/s at a settling time of 20 seconds. The simulation result shows a reduction in average intervehicle gap error of 0.15 m from the leader vehicle to the follower vehicles. An average velocity error of



0.13 m/s between the leader vehicle and followers. It also recorded an average acceleration of 0.73 m/s^2 and deceleration of 0.27 m/s^2 to achieve the desired steady state speed.

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