Cooperative Adaptive Cruise Control of Heterogeneous Vehicle Platoons

Erjen Lefeber[1], Jeroen Ploeg[1,2], Henk Nijmeijer[1]

[1] Dynamics and Control Group, Eindhoven University of Technology, [2] Cooperative Driving Group, 2getthere

Department of Mechanical Engineering

Contributions

- We present a one-vehicle look-ahead controller for CACC which allows for vehicle platoons that are heterogeneous with respect to the vehicle driveline
- No knowledge about the driveline dynamics of the preceding vehicle is required
- The controller generalizes a widely adopted controller for homogeneous strings
- The new controller performs at least as good as the original one, in terms of minimum string-stable time gap, settling time, and maximum jerk

Cooperative Adaptive Cruise Control

- Using wireless communication
- Short inter-vehicle distances without compromising string stability
- Increased road throughput, fuel efficiency

Problem in practice

- Difference in driveline characteristics
- Require knowledge of driveline dynamics of predecessor (may not be available)

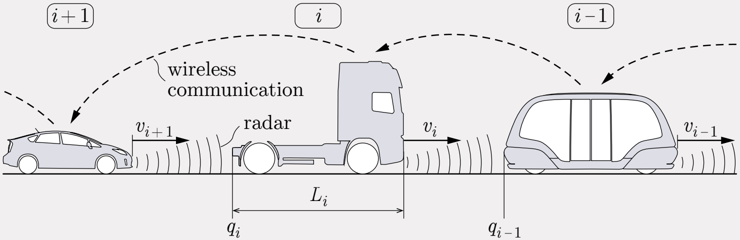
Existing literature

- Robustness approach / worst-case scenario (Shaw and Hedrick 2007; Gao et al., 2016; Al-Jhayyish and Schmidt, 2018)
- Adaptive control (Tao et al., 2019; Harfouch et al., 2018), Zhu et al., 2019)

This paper

- No knowledge of driveline dynamics of predecessor required

Problem setting



Dynamics:

$$\dot{q}_i = v_i$$
$$\dot{v}_i = a_i$$
$$\dot{a}_i = -\frac{1}{\tau_i} a_i + \frac{1}{\tau_i} u_i$$

Desired distance: $d_{\mathrm{r},i} = r_i + h_i v_i$

Spacing error: $e_i = (q_{i-1} - q_i - L_i) - (r_i + h_i v_i)$

Standard approach (Ploeg et al., 2011)

Dynamic input-output linearization for output e_i.
Defining $\varepsilon_i = \begin{bmatrix} e_i & \dot{e}_i & \ddot{e}_i \end{bmatrix}^T$ results in

$$\dot{\varepsilon}_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau_i} \end{bmatrix} \varepsilon_i + \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{\tau_i} \end{bmatrix} \underbrace{\left[h_i \dot{u}_i + u_i - \left(1 - \frac{\tau_i}{\tau_{i-1}}\right) a_{i-1} - \frac{\tau_i}{\tau_{i-1}} u_{i-1} \right]}_{\zeta_i}$$

Taking $\zeta_i = \begin{bmatrix} k_\mathrm{p} & k_\mathrm{d} & k_\mathrm{dd} \end{bmatrix} \varepsilon_i$, with $k_\mathrm{p} > 0$, $k_\mathrm{d} > 0$, $k_\mathrm{dd} > -1$, results in dynamic controller

$$\dot{u}_i = -\frac{1}{h_i} u_i + \frac{1}{h_i} \begin{bmatrix} k_\mathrm{p} & k_\mathrm{d} & k_\mathrm{dd} \end{bmatrix} \varepsilon_i + \frac{\tau_{i-1} - \tau_i}{h_i \tau_{i-1}} a_{i-1} + \frac{\tau_i}{h_i \tau_{i-1}} u_{i-1}$$

which for homogeneous setting ($\tau_i = \tau_{i-1}$) reduces to

$$\dot{u}_i = -\frac{1}{h_i} u_i + \frac{1}{h_i} \begin{bmatrix} k_\mathrm{p} & k_\mathrm{d} & k_\mathrm{dd} \end{bmatrix} \varepsilon_i + \frac{1}{h_i} u_{i-1}$$

New approach (this paper)

Static input-output linearization for output e_i (with stable internal dynamics). Defining $\epsilon_i = \begin{bmatrix} e_i & \dot{e}_i \end{bmatrix}^T$ and the internal dynamics state $z = v_{i-1} - v_i$, results in

$$\dot{\epsilon}_i = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \epsilon_i + \begin{bmatrix} 0 \\ -1 \end{bmatrix} \underbrace{\left[\frac{h_i}{\tau_i} u_i + \left(1 - \frac{h_i}{\tau_i}\right) a_i - a_{i-1} \right]}_{\xi_i}$$

$$\dot{z} = -\frac{1}{h_i} z + \frac{1}{h_i} \epsilon_{i,2} + a_{i-1}$$

Taking $\xi_i = \begin{bmatrix} k_\mathrm{p} & k_\mathrm{d} \end{bmatrix} \epsilon_i$, with $k_\mathrm{p} > 0$, $k_\mathrm{d} > 0$, results in controller

$$u_i = \frac{\tau_i}{h_i} \begin{bmatrix} k_\mathrm{p} & k_\mathrm{d} \end{bmatrix} \epsilon_i + \left(1 - \frac{\tau_i}{h_i}\right) a_i + \frac{\tau_i}{h_i} a_{i-1}$$

Summary

Standard controller: $\dot{u}_i = -\frac{1}{h_i}u_i + \frac{1}{h_i}\zeta_i + \frac{\tau_{i-1}-\tau_i}{h_i\tau_{i-1}}a_{i-1} + \frac{\tau_i}{h_i\tau_{i-1}}u_{i-1}$

New controller: $u_i = \frac{\tau_i}{h_i}\xi_i + \left(1 - \frac{\tau_i}{h_i}\right)a_i + \frac{\tau_i}{h_i}a_{i-1}$

where ζ_i respectively ξ_i can be chosen freely to stabilize the ε respectively ϵ dynamics.

- Standard controller needs τ_{i-1}, a_{i-1}, and u_{i-1}.
- New controller needs only a_{i-1}.

Observation

Standard controller can be obtained with new controller by using $\dot{\xi}_i = -\frac{1}{\tau_i}\xi_i + \frac{1}{\tau_i}\zeta_i$

- In hindsight: standard controller can be implemented using only a_{i-1}
- New controller is more general class of controllers.

Performance analysis

Parameters as in Ploeg et al., 2011:
$\tau_i = 0.1$[s], $h_i = 0.5$[s], $k_{\mathrm{p}} = 0.2$, $k_{\mathrm{d}} = 0.7$, $k_{\mathrm{dd}} = 0$. Latency: $\theta_i = 0.02$[s].

String stability complementary sensitivity $\Gamma_i(s)$ from v_{i-1} to v_i (or from a_{i-1} to a_i):

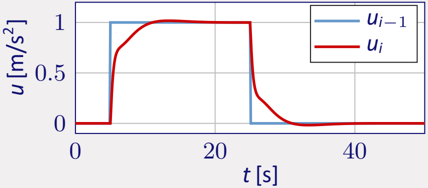
$$\Gamma_i(s) = \frac{1}{h_i s + 1} \frac{e^{-\theta_i s} s^2(\tau_{i-1}s + 1) + k_{\mathrm{dd}} s^2 + k_{\mathrm{d}} s + k_{\mathrm{p}}}{s^2(\tau_i s + 1) + k_{\mathrm{dd}} s^2 + k_{\mathrm{d}} s + k_{\mathrm{p}}}$$

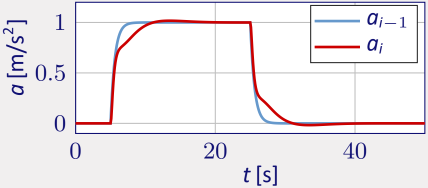
For string stability: $\|\Gamma_i(s)\|_{\mathcal{H}_\infty} \leq 1$

By increasing τ_{i-1}: $\|\Gamma_i(s)\|_{\mathcal{H}_\infty}$ arbitrarily large. For $\tau_{i-1} = 0.6$: $\|\Gamma_i(s)\|_{\mathcal{H}_\infty} = 1.8 > 1$

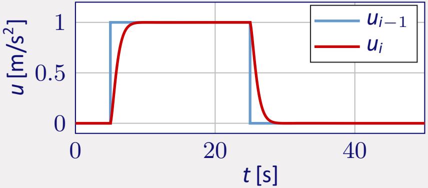
Performance analysis

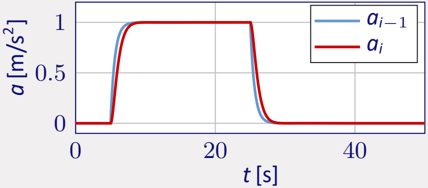
Standard controller ($\tau_i = 0.1$, $\tau_{i-1} = 0.6$)





Equivalent implementation using new controller (again: $\tau_i = 0.1$, $\tau_{i-1} = 0.6$)

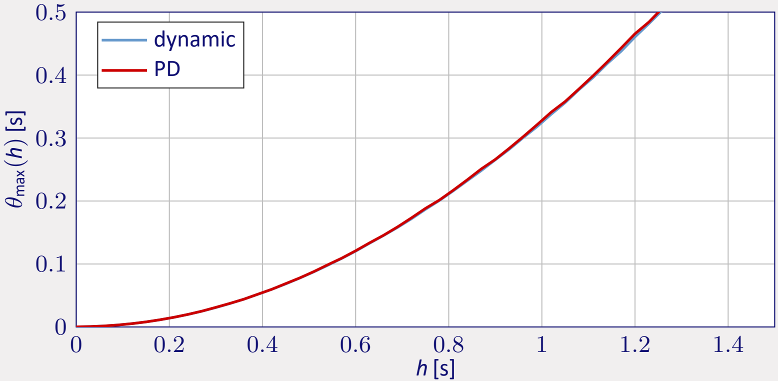




Performance analysis

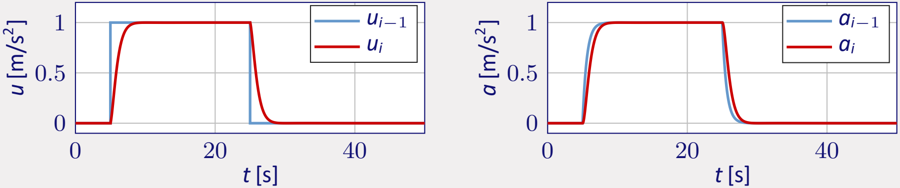
Controller $C(s) = (k_\mathrm{p} + k_\mathrm{d}s + k_\mathrm{dd}s^2) \cdot \frac{1}{\tau_i s+1}$: Settling time 1.81 s, max. jerk 1.35 m/s^3

Padé-approximant $C(s) = k_\mathrm{p} + (k_\mathrm{d} - k_\mathrm{p}\tau_i)s$: Settling time 1.82 s, max. jerk 1.35 m/s^3

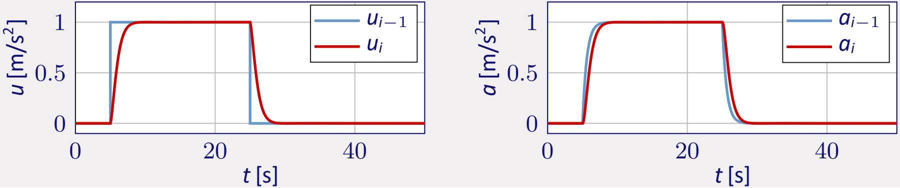


Performance analysis

Dynamic controller $C(s) = (k_\mathrm{p} + k_\mathrm{d}s + k_\mathrm{dd}s^2) \cdot \frac{1}{\tau_i s+1}$ $(\tau_i = 0.1, \tau_{i-1} = 0.6)$



PD controller $C(s) = k_\mathrm{p} + (k_\mathrm{d} - k_\mathrm{p}\tau_i)s$ $(\tau_i = 0.1, \tau_{i-1} = 0.6)$



Conclusions

- We presented a one-vehicle look-ahead controller for CACC which allows for vehicle platoons that are heterogeneous with respect to the vehicle driveline
- No knowledge about the driveline dynamics of the preceding vehicle is required
- The controller generalizes a widely adopted controller for homogeneous strings
- The new controller performs at least as good as the original one, in terms of minimum string-stable time gap, settling time, and maximum jerk