ENERGY-EFFICIENT COOPERATIVE ADAPTIVE CRUISE CONTROL OF PLATOONING VEHICLES

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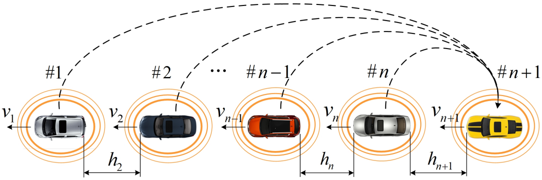
Background and Motivation



Background:

- There are over 1 million road traffic deaths worldwide every year.
- 90% of accidents are attributed to human errors
- Americans were stuck in traffic for 8 billion hours in 2015.
- "We are the first generation that can end poverty, the last that can end climate change." – Ban Ki-Moon.

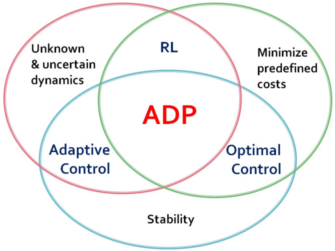
It's imperative to develop next-generation cruise controllers for connected vehicles to increase the safety, reliability, connectivity and autonomy.

[Challenge]:

1. Parametric variations → Unknown system parameters
2. Uncertain models of to-be-followed vehicles
3. Energy efficient → Eco-friendly
4. Input(acceleration) saturation

Background and Motivation

1. Adaptive control approaches for platooning vehicles are not optimal [Swaroop, Hedrick & Choi 2001], [Kwon & Chua 2014].
2. Optimal control methods are usually model-based and not data-driven. [Jovanovic & Bamieh 2005], [Waschl, Kolmanovsky, Steinbuch, & del Re 2014].
3. Reinforcement-learning-based controllers cannot guarantee the stability of the closed-loop systems [Ng *et al.* 2008], [Desjardins & Chaib-draa 2011]



We develop a data-driven, non-model-based adaptive optimal controller for platooning vehicles by Adaptive Dynamics Programming (ADP). The issue of input saturation is also addressed.

[1] Gao, W.; Jiang, Z. P. & Ozbay, K. Data-driven Adaptive optimal control of connected vehicles, *IEEE Transactions on Intelligent Transportation Systems*, 2016.

Background and Motivation

Dynamic Programming [Bellman 1957]

1. Curse of dimensionality
2. Curse of modeling

[Werbos 1968] pointed out that adaptive approximation to the HJB equation can be achieved by designing appropriate learning systems: approximate/adaptive dynamic programming (ADP)

1. Heuristic dynamic programming: approximate the optimal cost function.
2. Dual dynamic programming: approximate the gradient of the optimal cost function.

The platoon can be modeled by the following systems

$$\dot{x} = Ax + Bu$$
$$\mathcal{J}(x_0) = \int_0^\infty \left(x^T(\tau)Qx(\tau) + u^T(\tau)Ru(\tau)\right) d\tau$$

The optimal control policy

$$u = -R^{-1}B^T P^* x := -K^* x$$

where $P^* = P^{*T} > 0$ is the unique solution to Riccati equation

$$A^T P^* + P^* A + Q - P^* B R^{-1} B^T P^* = 0$$

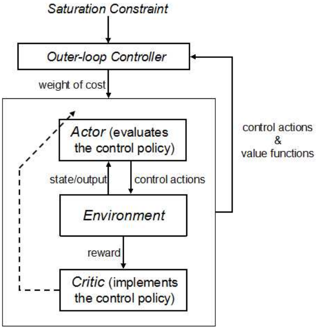
Adaptive optimal control: find P^* and K^* when A and B are unknown

- [Jiang & Jiang 2012] Adaptive optimal control with unknown system matrices A and B
  1. Start from an admissible K_0. $k \leftarrow 0$.
  2. $x^T(t_1)P_k x(t_1) - x(t_0)^T P_k x(t_0) = -\int_{t_0}^{t_1} x^T(Q + K_k^T R K_k)x d\tau + 2\int_{t_0}^{t_1}(u + K_k x)^T R K_{k+1} x d\tau$
  3. $k \leftarrow k+1$. Repeat Step 2.

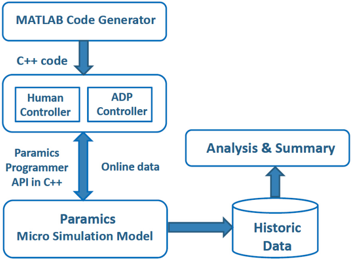
Both can ensure $\lim_{k\to\infty} P_k = P^*$ and $\lim_{k\to\infty} K_k = K^*$.

[2] Jiang, Y. & Jiang, Z. P. Computational adaptive optimal control for continuous-time linear systems with completely unknown dynamics, *Automatica* , 2012, 48, 2699-2704.

Paramics Micro-Traffic Simulation Results



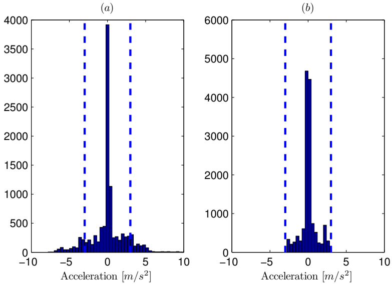
Double-loop ADP algorithm



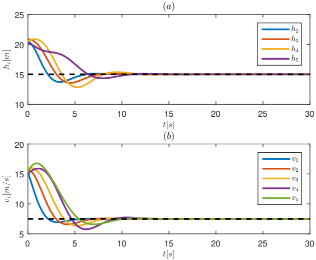
Traffic simulation architecture

[1] Gao, W.; Jiang, Z. P. & Ozbay, K. Data-driven Adaptive optimal control of connected vehicles, *IEEE Transactions on Intelligent Transportation Systems*, 2016.

Paramics Micro-Traffic Simulation Results

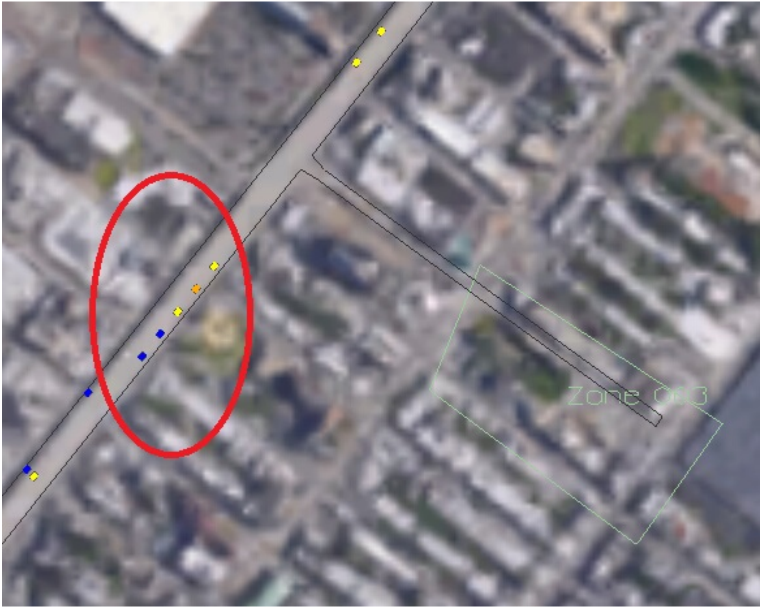


Histograms of accelerations



Plots of headways and velocities

Paramics Micro-Traffic Simulation Result



Nonlinear and Adaptive Optimal Control of Platooning Vehicles

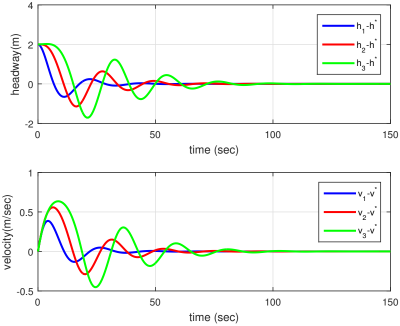
Employ global ADP (GADP)[Jiang and Jiang 2015] to solve a longstanding issue in ITS: how to take into account strong nonlinearity and unknown dynamics in the design of global adaptive optimal controllers.

Contributions:

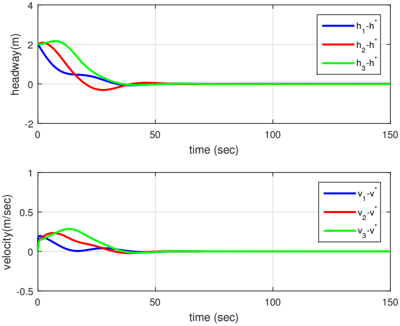
- Because of the strongly nonlinear dynamics of the platooning vehicles, we are not aware of any global solutions to adaptive optimal control of platooning vehicles with unknown dynamics.
- Different from existing adaptive control approaches of platooning vehicles [Swaroop, Hedrick & Choi 2001], [Kwon & Chua 2014] the online GADP approach learns a near-optimal controller iteratively via real-time state/input data.
- The neural network approximation is avoided for this kind of high-order platooning vehicle systems which dramatically decreases the computational burden.

[3] Gao, W. & Jiang, Z. P., Nonlinear and Adaptive Suboptimal Control of Connected Vehicles: A Global Adaptive Dynamic Programming Approach. *Journal of Intelligent & Robotic Systems*, 2016.

Nonlinear and Adaptive Optimal Control of Platooning Vehicles



Initial control policy



Learned control policy

Nonlinear and Adaptive Optimal Control of Platooning Vehicles

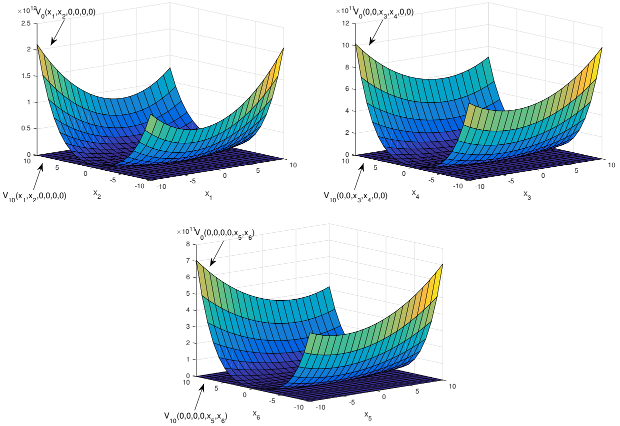


Figure: Comparison of value functions V_0 w.r.t. the initial control policy and V_{10} w.r.t. the learner control policy

Thanks!

Supplimental slides: Model of Vehicles

The optimal velocity model [Orosz, *et al.*, 2010] of the ith human-driven vehicle is

$$\begin{aligned} \dot{h}_i &= v_{i-1} - v_i, \\ \dot{v}_i &= \alpha_i(f(h_i) - v_i) + \beta_i \dot{h}_i, \end{aligned} \tag{1}$$

where $i = 2, 3, \cdots, n$. α_i and β_i are human parameters with α_i the headway gain and β_i the relative velocity gain satisfying $\alpha_i > 0, \alpha_i + \beta_i > 0$. $f(\cdot)$ indicates a range policy

$$f(h) = \begin{cases} 0 & \text{if} \quad h \leq h_s, \\ v_m(1 - \cos(\pi \frac{h-h_s}{h_g-h_s}))/2 & \text{if} \quad h_s < h < h_g, \\ v_m & \text{if} \quad h_g \leq h. \end{cases} \tag{2}$$

which implies that the vehicle i remains standstill if $h_i \leq h_s$. v_i increases as h_i increases in the range (h_s, h_g). Additionally, if $h_i \geq h_g$, vehicle i aims to travel at the maximum velocity v_m. In this paper, the goal for each driver is to actuate the vehicle at desired headway h^* and velocity $v^* = f(h^*)$.