Project 2

Cooperative platooning cruise control

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Abstract

This project aims at designing and implementing a cooperative platooning cruise control, that allows a group of cars to follow a leader car, maintaining the distance between them at a constant desired set-point, reacting to possible changes in the environment conditions. The project builds on the first project of the course, and defines goals for the project to achieve in terms of distributed control, going from a centralized setup with all the vehicle in a single model, to a distributed cooperative setup. The final goal is to explore the behavior of the distributed closed-loop system considering advanced analysis and problems in real-world situations that involve reaction to a road hazards.

1 Introduction

Autonomous driving cars are still a technology under intense development, where the safety and security concerns require that the developed systems have proven performance and stability. As this is a complex task, several car makers have began to offer partial autonomy systems as assistive technologies to a human driver. Among them we can find the adaptive cruise control, assisted lane switching, and assisted parking. Nonetheless, the cooperation of different cars toward a higher traffic efficiency (e.g., in rush hours), is still a problem far from deployment in the car industry. In this project you build on the knowledge you gained in the Project 1, further considering the problem of cooperative platooning cruise control (CPCC), as depicted in Figure 1, which aims at regulating the distance of the autonomous car to the next car for a set of n-cars in a cooperative setup.

1.1 Learning outcomes

This project assignment will help you to achieve the following learning outcomes:

- Model and analyze a cooperative cruise control system as one or several state-space models.
- Design a distributed cooperative MPC strategy for a platoon of cars.
- Redesign the distributed MPC controller considering the constraints of the system and real-world operation.
- Analyze the influence of the network topology and communication delays.

1.2 Organization

The project assignment will take place in six sessions. Each group is expected to prepare each session in advance, by making the necessary theoretical computations and preparing the necessary Matlab code.

The evaluation of this work has three components totaling 35% of the final grade):

1. Draft paper: complete Section 2, submited through moodle by 16/12/2021 (5%),
2. Final paper and code (20%): Moodle submition by 03/01/2022 (20%),
3. Online presentation: during TP class time, on 06/01/2022, 10 minutes for each group presentation + 5 minutes for Q&A (10%).

The draft and final paper[1], must provide the reasoning behind all choices made during the project and the discussion of how the results address the requested goals. Nonetheless, the paper should be as concise as possible. You can write in English or in Portuguese and use any editor of your choice (MS word, Latex, handwritten, etc), but the final paper should be a PDF file. The paper (draft and final) along with the Matlab code used to obtain the results should be submitted through Moddle.

[1] A paper template in LaTeX is provided at `https://www.overleaf.com/read/yhjyyswtykqc`.

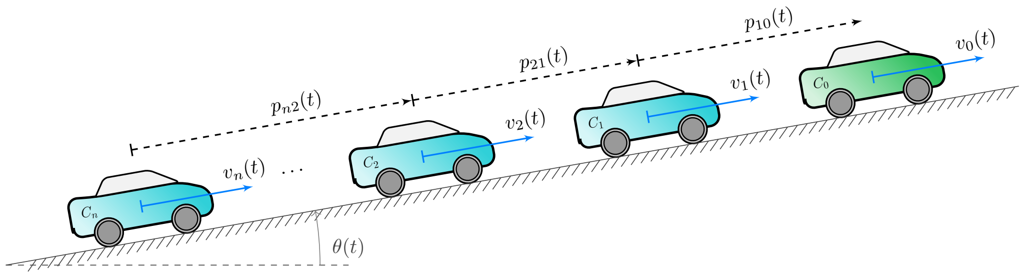

Figure 1: Schematic of two car automatic cruise control system.

1.3 Ethics

In light of true academic freedom, students can and should discuss their ideas and approaches freely with other students, teachers, or the community at large. Nonetheless, the reports submitted by the students must be **original** and correspond to their **actual work**, following a widely accepted academic ethics code, also detailed in the *Código de Ética da Universidade Nova de Lisboa* (`https://www.fct.unl.pt/sites/default/files/UNL_Codigo_etica.pdf`). Automatic verification tools, such as Turnitin, might be used upon submission.

2 Two-follower problem

In this project builds on the strategies and results of Project 1, which designed an adaptive cruise control based on MPC techniques for one car, which enables the follower to maintain a safe distance from a preceding car.

In particular, the goal is to track a given distance reference considering the distance between the cars i and j, denoted as $p_{ji}(t) := p_i(t)-p_j(t)$, where $p_j(t)$ is the position of the follower car and $p_i(t)$ the position of the preceding car. This is done by changing the throttle of the follower car, which enables the control of the force that the engine generates, denoted as $f_j(t)$. As in the first project, the cars are also under the influence of the wind speed, $v_w(t)$, and slope of the road, $\theta(t)$, while the friction forces on the tires is considered negligible. A summary of parameters is provided in Table 1, while the main variables are also given below:

- $p_{ji}(t)$ – dist. between the cars j and i [m]
- $p_i(t)$ – position of vehicle $i = 1, \ldots, n$ [m]
- $v_i(t)$ – speed of vehicle i [m/s]
- $f_i(t)$ – force generated vehicle i [N]

Parameter	**Symbol**	**Value**
mass	m	$1500\ kg$
drag coefficient	C_d	0.3
frontal area	A	$1.8\ m^2$
air density	ρ	$1.225\ kg\,m^{-3}$
gravity accel.	g	$9.8065\ m\,s^{-2}$
typical slope	θ_e	$5\%; 0.05\ rad$
max. (engine) force	f_{max}	$2800\ N$
min. (brake) force	f_{min}	$-2200\ N$
max. force var.	Δf_{max}	$200\ N$
max. slope	θ_{max}	$10\%; 0.1\ rad$
desired distance	d_r	$10\ m$
min. distance	d_{min}	$3\ m$
typ. leader speed	v_{0_e}	$25\ m/s$
typ. wind speed	w_e	$0\ m/s$

Table 1: Parameters for the car models.

- $p_0(t)$ – position of the leader vehicle [m]
- $v_0(t)$ – speed of the leader car [m/s]
- $w(t)$ – wind speed [m/s]
- $\theta(t)$ – road slope [rad]

The main objective of this section is to develop teh centralized an decentralized strategies for the two-follower problem for platooning cruise controller. Consider the following steps towards this goal:

2.1 Considering the work developed in Project 1, deduce the individual and joint state-space discrete-time LTI models for the two follower cars, considering the state-space vectors (before linearization), $x_1(t) = \begin{bmatrix} p_{10}(t) \\ v_1(t) \end{bmatrix}$ and $x_2(t) = \begin{bmatrix} p_{21}(t) \\ v_2(t) \end{bmatrix}$.

2.2 Compute the batch version of these models.

2.3 Define centralized and decentralized MPC problems for the two-follower case.

2.4 Simulate the closed-loop systems, adjusting the controller and simulation parameters to highlight the differences between the two strategies and reactions to external disturbances.

3 Distributed platooning

Building on the above centralized and decentralized MPC controllers, we want now to implement a distributed control strategy that takes into account the physical and operation constraints of the system.

Consider the following limitations for the adaptive cruise control, where the necessary parameters are defined in Table 1:

- Engine force:

$$f_{min} \leq f_i(k) \leq f_{max}$$

- Engine force variation:

$$-\Delta f_{max} \leq \Delta f_i(k) \leq \Delta f_{max}$$

- Distance to leader car:

$$p_{ji}(k) \geq d_{min}$$

3.1 Define the centralized and decentralized MPC problem considering the previous cost, the state equations, and the above input and state constraints.

3.2 Define the equivalent distributed cooperative MPC problem.

3.3 Implement and simulate the closed-loop systems for these strategies, discussing and illustrating the differences between them.

Hint: Start with the unconstrained control problem and progressively add the input, input variation, and output constraints, obtaining the best response with the viable constraints to get feasible results.

4 Advanced analysis

This section consider more advanced problems that may arise in distributed versions of MPC, in particular when having a significant number of cars (≥ 10) and considering abrupt changes in the leader velocity. It is left up to you to decide what to address, considering the following points as suggestions, but not limiting the scope to just these topics.

(a) What are the effects of the network topology? For instance, if all cars can get information from the leader car, versus if they can only get information from the car in from of them.

(b) What are the effects of external disturbances, such as the wind speed or the slope of the terrain?

(c) What if we have delays in the communications between cars (more than a sampling time)?

(d) How to ensure the stability of the distributed approach?

Note that some of these topics might need further reading beyond the scope of this course, such as the work presented in [6, 2].

References

[1] F. Borrelli, A. Bemporad, and M. Morari. *Predictive Control for Linear and Hybrid Systems*. Cambridge, 2017.

[2] Henrique Ferraz and João P. Hespanha. Iterative algorithms for distributed leader-follower model predictive control. In *2019 IEEE 58th Conference on Decision and Control (CDC)*, pages 3533–3539, 2019.

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[4] J. Rawlings, D. Mayne, and M. Diehl. *Model Predictive Control: Theory, Computation, and Design*. Nob Hill, 2nd edition, 2017.

[5] Liuping Wang. *Model Predictive Control System Design and Implem. Using MATLAB*. Springer, 2009.

[6] Y. Zheng, S. E. Li, K. Li, F. Borrelli, and J. K. Hedrick. Distributed model predictive control for heterogeneous vehicle platoons under unidirectional topologies. *IEEE Transactions on Control Systems Technology*, 25(3):899–910, 2017.