Artificial Potential Functions for Control of Automated Vehicles

E. Semsar-Kazerooni*, J. Ploeg*, K. Elferink**, and H. Nijmeijer **
**Integrated Vehicle Safety Department, TNO, Helmond, Netherlands*
***Department of Mechanical Engineering, Eindhoven University of Technology, Netherlands*

Summary. In this abstract, a nonlinear vehicle-following control strategy is presented. With a proper choice of an artificial potential function, in addition to vehicle following, other requirements in terms of a smooth gap closing and collision avoidance are embedded in the control design. The choice of a specific controller associated with the selected potential function is motivated through evaluating performance metrics. The controller which has an overall best performance in terms of these metrics is used to realize the objectives of vehicle following, gap closing, and collision avoidance in a vehicle platoon.

Introduction

The Cooperative Adaptive Cruise Control (CACC) [1] is a vehicle-following control technology which was enabled by introduction of vehicle-2-vehicle (V2V) communication. This technology aims at maintaining a small inter-vehicle distance in a vehicle platoon. The application of these systems can increase road capacity, and potentially reduce the number of traffic jams and their length [2]. However, the state-of-the-art CACC strategies are dealing with vehicle following, only, and are not designed for other functionalities such as smooth gap closing or collision avoidance. However, a nonlinear multi-objective control strategy should enable integrating several control objectives in a single design. Control design using artificial potential functions (APF) is a good candidate for this purpose, as will be elaborated in this abstract.

Problem statement

In this abstract, we will study a vehicle platoon as depicted in Fig. 1. First, we briefly describe the platoon dynamics as presented in [1, 3]. Consider a vehicle platoon, as shown in Fig. 1, where d_i is the distance between vehicle i and its preceding vehicle $i-1$, u_{i-1} is the input (desired acceleration) of vehicle $i-1$, and v_i is the velocity of vehicle i. The main objective of each vehicle in the platoon (except the lead vehicle) is to regulate d_i to $d_{r,i}$, where $d_{r,i}(t) = r_i + hv_i(t)$, h is the time gap, r_i is the standstill distance, and $i = 1, \dots, m$, with m being the number of vehicles in the platoon. For control design, the following longitudinal vehicle dynamics model is adopted

$$\mathcal{P}: \quad \begin{pmatrix} \dot{s}_i \\ \dot{v}_i \\ \dot{a}_i \end{pmatrix} = \underbrace{\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau} \end{pmatrix}}_{A} \begin{pmatrix} s_i \\ v_i \\ a_i \end{pmatrix} + \underbrace{\begin{pmatrix} 0 \\ 0 \\ \frac{1}{\tau} \end{pmatrix}}_{B} u_i, \tag{1}$$

where s_i is the position of the rear bumper and, a_i is the acceleration of vehicle i, and τ is a time-constant representing driveline dynamics. Using the spacing error $e_i(t) := d_i(t) - d_{r,i}(t)$ and its higher derivatives as the system states, the dynamic controller $\dot{u}_i = -\dfrac{1}{h}u_i + \dfrac{1}{h}\bar{u}_i$ is introduced, where $\bar{u}_i$ is a new input [1]. Now, the question is how to design a stabilizing controller $\bar{u}_i$ which accommodates two additional requirements, being smooth gap closing and collision avoidance. This is done through design of a proper potential function which will be later on used for derivation of a controller, as will be explained in the next section.

Controller design using APF

In [3], the vehicle-following control design was addressed using an APF and by introducing a transformation in error state coordinates. The choice of a specific controller corresponding to that potential function is motivated here by providing a comparison between few possible options for the controller. Towards this, let us consider the following potential function

$$\Psi_A(x) = \Psi_{RP}(x) + \Psi_{AP}(x) \tag{2}$$

where two distinct terms corresponding to a Repulsive Potential (RP) and an Attractive Potential (AP) are introduced. Here, x can represent any relevant state of the system, e.g., position or velocity error, or any combination of these which

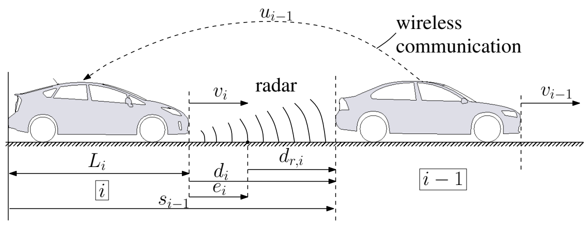

Figure 1: Side-view of a CACC-equipped vehicle platoon.

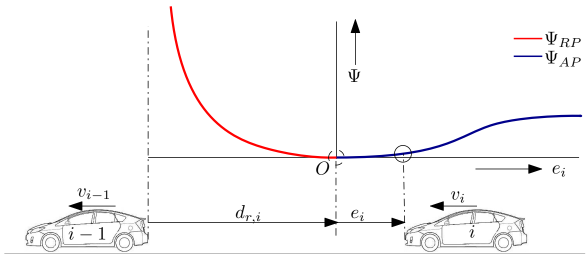

Figure 2: The desired repulsive and attractive potential (Ψ_{RP}, Ψ_{AP}) for a vehicle-following control design problem

Table 1: Performance evaluation in platooning (P) and gap-closing (GC) scenarios

Vehicle	$P:Q_1$	$P:Q_2$	$GC:Q_1$	$GC:Q_3$
PD control	2.3412	3.9860	4.3501	106.8886
APF1 control,	2.5264	3.3596	1.1164	286.0787
APF2 control,	2.5264	3.3596	2.6978	168.9997
APF3 control	2.2365	1.9516	2.4825	191.9660

should be regulated to a desired value. For illustration, these repulsive and attractive potential functions (Ψ_{RP}, Ψ_{AP}) are sketched in Fig. 2. In this example, it is assumed that $x = e_i$. In case $e_i \ll 0$, a collision is imminent, therefore the repulsive potential increases rapidly along the red curve, being the collision avoidance function. For a positive value of the error, a smooth gap closing behavior is desirable. Therefore, the potential function changes smoothly along the blue curve. To obtain the desired performance requirements, a potential function consisting of a polynomial (attractive part) and an exponential term (repulsive part) can be used. Subject to this choice of potential function, there are a number of choices for the possible control strategy. Three of the most relevant choices are listed below, where $D(e_i)$ is a nonlinear damping coefficient and $x_i := e_i + c\dot{e}_i$:

$$\textit{APF1:} \qquad \bar{u}_{i,APF1} = \frac{\partial \Psi_A(e_i)}{\partial e_i} + k_d \dot{e}_i + u_{i-1}, \tag{3}$$

$$\textit{APF2:} \qquad \bar{u}_{i,APF2} = \frac{\partial \Psi_A(e_i)}{\partial e_i} + D(e_i)\dot{e}_i + u_{i-1}, \tag{4}$$

$$\textit{APF3:} \qquad \bar{u}_{i,APF3} = \frac{\partial \Psi_A(x_i)}{\partial x_i} + u_{i-1}, \quad 2 \le i \le m. \tag{5}$$

Performance criteria

For a vehicle-following scenario, there is a desire to minimize changes in acceleration for fuel consumption and comfort purposes. This can be reflected by using an integral square error (ISE) criterion for acceleration profile, i.e. $Q_{1,i} = ||a_i(t)||_2$. Since safety and tracking are additionally of importance, the position error is evaluated using the infinity norm, i.e. $Q_{2,i} = ||e_i(t)||_\infty$. For the gap closing scenario, it is important to reduce the corresponding time required to close the gap while the acceleration changes are minimized. Therefore, the $\mathcal{L}_1$ norm of the position error is considered, i.e. $Q_{3,i} = \int |e_i(t)|dt$. Using two scenarios of vehicle-following and gap closing and with these three performance criteria, the controller choices are examined. Table 1 summarizes the performance indices for three proposed controllers in (3) as well as the PD controller designed in [1]. It can be seen from Q_1 in the gap-closing scenario that controller *APF1*, has the best performance in minimizing accelerations, however, it closes the gap very slowly, as indicated by the relatively high value of Q_3. Controllers *APF2* and *APF3*, are more reasonably balanced between limiting the gap-closing time and the acceleration levels. It can be seen that the controller *APF3* has the best performance in the platooning test, and is one of the best options in gap closing. Although the presented values for Q_i depend on the particular scenario parameters, the choice of control structure *APF3* can be motivated subject to the proposed scenario parameters.

Conclusion

In this abstract, the concept of APF-based control design is explored. Some control structures have been introduced and compared using three performance criteria. The design objectives for these controllers were vehicle-following, collision avoidance, and smooth gap closing. The best performed option is chosen for further analysis and verifications.

References

[1] J. Ploeg, N. van der Wouw, and H. Nijmeijer, "$\mathcal{L}_p$ string stability of cascaded systems: Application to vehicle platooning," *IEEE Trans. Control Syst. Technol.*, vol. 22, 2014.

[2] S. E. Shladover, "Automated vehicles for highway operations (automated highway systems)," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 219, no. 1, pp. 53–75, 2005.

[3] E. Semsar-Kazerooni, J. Verhaegh, J. Ploeg, and M. Alirezaei, "Cooperative adaptive cruise control: An artificial potential field approach," in *IEEE Intelligent Vehicles symposium*, 2016, pp. 361–367.