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Digital idle speed control of automotive engines: A safety problem for hybrid systems☆

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Abstract

We address the idle speed control problem in automotive electronics using hybrid methods to derive a digital control law with guaranteed properties. Associating a switching system with the hybrid system that describes the engine operation is crucial to developing a computationally feasible approach. For switching systems with minimum and maximum dwell times and controlled resets, we are able to derive digital control strategies with guaranteed properties that ensure safety. The proposed methodology, while motivated by the idle control problem, is of general interest for hybrid systems for which minimum and maximum dwell times can be established. In our modeling approach, we do not assume synchronization between sampling time and switching time. This is an important technical aspect in general, and in particular for our application, where there is no reason why sampling and switching should be synchronized. Some simulation results are included to demonstrate the effectiveness of the approach.

Keywords: Idle speed control; Hybrid systems; Switching systems; Safety; Digital control

1. Introduction

Applications of hybrid systems techniques to automotive control have been extensively pursued (see [1,2,7]). These models are required to achieve better control accuracy since the internal combustion engine of a car is intrinsically a hybrid system due to (i) the discrete nature of the four-stroke engine cycle; (ii) the transitions between strokes that are determined by the

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continuous motion of the driveline, which in turn depends on the torque produced by each piston, the actual gear engaged and the connection clutch state. While accurate, the hybrid engine model is complex for control design purposes and may have stability properties that are difficult to analyze. Fortunately, the peculiarities of the engine control problems in each of its working regions (e.g., idle, speed tracking, cut-off) allow simplifications that yield effective control strategies. The idle control problem is one of the most interesting challenges in automotive control and is the motivation for this paper.

The idle speed control problem consists of finding a control strategy that maintains, while in the idle mode, the engine speed in a given range, rejecting torque disturbances due to accessory loads (such as the air-conditioning system and the steering wheel servo-mechanism), and preventing the engine from stalling. This is a typical safety problem where a control strategy has to be studied so that the controlled system never reaches a set of 'bad' states. Due to the unpredictable behavior of the torque loads and to the engine operating at very low engine speed, the synthesis of a suitable idle control strategy poses serious challenges to the control designer and makes the idle speed problem hard. We focus on *digital (discrete-time) control laws* since in automotive applications the control strategies are implemented in Engineering Control Units (ECU) that are based on one or more microcontrollers carrying out the computation needed for the control strategies. Traditional techniques used mean-value models (see [4] for a comprehensive list of references related to the idle control problem) that did not capture important transient behaviors. In [3], by using a simplified hybrid model, a control synthesis procedure was proposed based on the computation of the maximal safe set, i.e., the set of all initial conditions starting from which the evolution of the system stays inside the desired range. Once the maximal safe set is computed, following the procedure in [15], it is always possible to derive the *maximal controller*, i.e. the set of all possible control strategies that solve the given problem. However, the resulting control synthesis techniques were still too complex from an industrial point of view, since tuning the controller to different car models required extensive manual recomputation of the control strategy by control engineers.

In [4], a different approach based on a divide and conquer methodology was proposed. First, the overall control system was divided into subparts; then a control strategy for each block in isolation was designed, assuming that the remaining parts can be controlled so that the desired behavior for the whole system was guaranteed. Finally, the correctness of the assumptions made on each subsystem is verified, so that the closed-loop system is guaranteed to behave correctly on the whole.

In [5], starting from a slightly simplified version of the model in [4],[1] we addressed the idle speed control problem from a different perspective: instead of synthesizing a particular control law to be subsequently verified, our methodology was based as in [3] on the computation of the maximal safe set, and carried out using efficient and portable algorithms in the discrete-time domain [9]. However, while this method gave a satisfactory 'practical' solution to the problem, the important question of what were the properties of the control strategy when applied to the hybrid system with *continuous* dynamics remained unanswered.

In this paper, we extend the theoretical results obtained in [10] to solve the idle speed control problem, by guaranteeing that the continuous-time dynamics satisfy the constraints. Our strategy is to associate an approximating switching system with the hybrid system under consideration. This is possible in cases where, as in the idle control case, we know that the system 'dwells' in

[1] We do not consider the throttle valve dynamics, assuming that it is fast enough to be neglected compared to the manifold and powertrain dynamics.