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Predictive energy management of hybrid long-haul trucks

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ABSTRACT

This paper presents a novel predictive control scheme for energy management in hybrid trucks that drive autonomously on the highway. The proposed scheme uses information from GPS together with information about the speed limits along the planned route to schedule the charging and discharging of the battery, the vehicle speed, the gear, and when to turn off the engine and drive electrically. The proposed control scheme divides the predictive control problem into three layers that operate with different update frequencies and prediction horizons. The top layer plans the kinetic and electric energy in a convex optimization problem. In order to avoid a mixed-integer problem, the gear and the switching decision between hybrid and pure electric mode are optimized in a lower layer in a dynamic program whereas the lowest control layer only reacts on the current state and available references. The benefits of the proposed predictive control scheme are shown by simulations between Frankfurt and Koblenz. The simulations show that the predictive control scheme is able to significantly reduce the mechanical braking, resulting in fuel reductions of 4% when allowing an over and under speed of 5 km/h.

1. Introduction

Hybrid Electric Vehicles (HEVs) have in recent years been introduced as passenger cars and city buses. A hybrid powertrain saves fuel by regenerating brake energy with an electric machine and battery and by turning the engine off when battery energy is abundant and the power request is low enough for pure electric driving. With the ongoing development towards more reliable and cheaper batteries, hybridization is an emerging technology for heavy-duty trucks that drive in hilly or lightly hilly terrain.

In addition, the significant mass of heavy-duty trucks means that they have an inherent capability to store a large quantity of kinetic energy; by allowing the speed to vary within a relatively narrow interval, the vehicle kinetic energy can be used as an efficient energy storage. Building up speed when going downhill is preferable compared to regenerating brake energy into the battery due to decreased wear and losses in the battery and electric machine.

Several manufacturers currently provide intelligent cruise controllers for conventional trucks that save fuel by utilizing information about the upcoming topography, controlling the speed over a receding horizon. Typically, these cruise controllers reduce the speed while climbing uphill and then switch to neutral when rolling over the crescent and during the downslope. This behavior can be implemented with heuristic control strategies when the topographic profile is relatively simple. For more complex topographic profiles, with successive hills of different shapes, model based control is the preferred implementation where the energy use is coordinated by an optimal control algorithm. A real-time implementable Dynamic Programming (DP) algorithm (Bellman & Dreyfus, 1962) that decides the gear shifts and the vehicle speed for conventional trucks is presented in Hellström, Ivarsson, Åslund, and Nielsen (2009) and Hellström, Åslund, and Nielsen (2010a). The DP algorithm is able to enforce a constraint on the trip time and achieves close to optimal fuel consumption for all types of topographic profiles.

However, DP suffers from the curse of dimensionality (Bertsekas, 2000), which means that computation time grows exponentially with increased number of dynamic states and control signals. With the advent of hybrid electric heavy-duty trucks, this impediment is more restrictive, since the control algorithm has to coordinate both the kinetic and electric energy of the vehicle. To avoid the high computational requirement of a DP algorithm with both kinetic and electric energy as states as in Hellström, Åslund, and Nielsen (2010b), Van Keulen, Foster, de Jager, and Steinbuch (2010) and Van Keulen, de Jager, and

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Steinbuch (2011) propose the idea of adjoining the system dynamics to the objective, while simplifying the problem by disregarding engine on/off and clutch opening, and approximating the discrete-gear transmission to a continuously variable transmission. The drawback of this strategy is that (1) it is difficult to derive analytical expression when more system dynamics are being considered and (2) analytical solution can be obtained only when buffers are not operated at their energy limits.

This paper presents a hierarchical control architecture that divides the predictive control problem into two predictive control layers that operate with different update frequencies and prediction horizons. The top layer plans the speed and battery energy trajectory with a Direct Optimal Control algorithm (Bertsekas, 2000; Betts, 2010), where in order to avoid a mixed-integer problem, the gear and engine on/off are not explicitly modeled with integer variables. The approach is instead to model the force acting on the wheels as the sum of three optimization variables: the force that can be delivered from the engine on the preferred cruise gear,[1] the remaining force that can be delivered from the engine at any lower admissible gear, and finally the force from the electric machine. By assigning a lower efficiency to the torque delivered at lower gears, the controller will try to limit the acceleration to what can be delivered on the preferred cruise gear. In the Direct Optimal Control algorithm the optimal control problem is transcripted into a finite-dimensional Non-Linear Program (NLP) through discretization of both control and state variables.

The low hierarchy predictive control layer decides gear and engine on/off using information from the speed and battery energy state and costate trajectories originating from the top control layer. The algorithm in the low hierarchy predictive control layer is an extension of the ideas presented in Johannesson, Pettersson, and Egardt (2009), which use DP to plan the engine on/off for an HEV city bus based on several possible speed profiles. Since the focus in this paper is on cruise control on highways only one speed profile is required.

The main research contribution in the paper is the modeling steps in the Direct Optimal Control algorithm in the top predictive control layer which makes the NLP either a convex Quadratic Program (QP) or a convex Second Order Cone Program (SOCP) (Boyd & Vandenberghe, 2004). The SOCP formulation has the advantage of more accurately modeling the battery losses and the travel time, but problem convexity can only be proved for the special case when the electric auxiliary power load always exceeds the maximum battery loss. On the other hand, the QP formulation can rely on more mature solvers and lower computation time.

Outline: The objective of the paper is described in Section 2. Section 3 presents the decentralized, hierarchical control scheme with a brief description of the control algorithm in the low hierarchy predictive control layer. The modeling steps and the transcription in the Direct Optimal Control algorithm in top control layer are described in Section 4. The predictive control scheme is then tested in a simulation study in Section 5. The contribution is finished with discussions in Section 6 and conclusions and future work in Section 7.

2. Objective

A prevalent goal of this paper is to deliver a model predictive control scheme that maximizes a vehicle's energy efficiency in real-time operation. The objective is stated as a minimization of a weighted criterion of fossil fuel and comfort penalties over a segment from distance s_0 to distance s_f, satisfying certain requirements. In the remainder of the paper, it is assumed that cruise control is active during the segment from distance s_0 to distance s_f, thus enabling semi-autonomous vehicle operation where the only manually controlled actuator is the steering wheel. We propose a decentralized and hierarchical predictive control scheme, further detailed in Section 3. This paper focuses on the Direct Optimal Control algorithm in the top layer in the hierarchy, which delivers reference trajectories for the main energy buffers using predictive information. For completeness, the other control layers are briefly described and the problem is first formulated in a broad, more general form.

The nomenclature used in the paper is as follows: the symbols F, P, and E describe force, power and energy, respectively, while the subscripts V, E, M, T, B and A describe vehicle, internal combustion engine, electric machine, transmission, battery and auxiliaries, respectively. The subscript d is added to denote dissipative terms. The vehicle velocity, v, and the signals describing force, power and energy are functions of time or distance, although explicit notation is at some places omitted for improved readability. The time derivative of a variable $x(t)$ is written as $\dot{x}$.

2.1. Vehicle model

The modeling details that are most relevant to this study include a lumped mass vehicle model and a comprehensive powertrain model. The model consists of two real valued dynamic states: the vehicle velocity, v, and the battery energy, E_B. Moreover, the model has a discrete valued state, x_T, that include the transmission gear in the Automated Manual Transmission (AMT), engine on/off/idle mode and a gear transition mode. Hence, the vehicle model is a hybrid system, with the discrete valued decision variable u_T (i.e. the set $\mathcal{U}_T$ is discrete) that control gear and mode switching.

The longitudinal vehicle dynamics are modeled as

$$m_e \dot{v} = F_V - F_{Vd}(v, \alpha(s)) - mg \sin \alpha(s) \tag{1}$$

where F_V is the total wheel force, v is the longitudinal speed, α is the road gradient, s is the traveled distance, g is the gravitational acceleration, m is the vehicle mass and m_e is the equivalent mass that includes the actual vehicle mass and terms reflecting inertia of rotational components. The vehicle is subject to dissipative (retarding) forces

$$F_{Vd} = \frac{\rho_a A_f c_d}{2} v^2 + mgc_r \cos \alpha(s) \tag{2}$$

consisting of the aerodynamic drag and the rolling resistance. A description of the coefficients and their values used in the longitudinal dynamics relation is given in Table 1.

The vehicle powertrain includes an internal combustion engine (ICE) and an electric machine (EM) coupled in a parallel configuration, illustrated in Fig. 1. The parallel configuration allows direct transmission of mechanical power from the ICE and/or EM to the wheels. This mechanical power balance equation is

$$P_E + P_M - P_{brk} = F_V v + P_{Td}(x_T, P_E, P_M, u_T) \tag{3}$$

where P_{Td} constitutes all energy losses arising from gear shifts and transitions between engine on/off/idle mode and $P_{brk} \geq 0$ is the brake power from the mechanical brakes. The EM can be operated as a generator, i.e. $P_M < 0$, when F_V is negative, or when the ICE produces excess power. Remaining braking energy that is not recuperated by the EM is either dissipated as friction losses in the ICE, when $P_E < 0$, or as a heat produced when applying the braking pads.

[1] For trucks manufactured for the European market, this would typically be the highest gear when driving on the highway.