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Real-time predictive control strategy for a plug-in hybrid electric powertrain ☆

Amir Taghavipour *, Nasser L. Azad, John McPhee

Systems Design Engineering Department, University of Waterloo, 200 University Ave. W, Waterloo, Ontario, Canada

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ABSTRACT

Model predictive control is a promising approach to exploit the potentials of modern concepts and to fulfill the automotive requirements. Since, it is able to handle constrained multi-input multi-output optimal control problems. However, when it comes to implementation, the MPC computational effort may cause a concern for real-time applications. To maintain the advantage of a predictive control approach and improve its implementation speed, we can solve the problem parametrically. In this paper, we design a power management strategy for a Toyota Prius plug-in hybrid powertrain (PHEV) using explicit model predictive control (eMPC) based on a new control-oriented model to improve the real-time implementation performance. By implementing the controller to a PHEV model through model and hardware-in-the-loop simulation, we get promising fuel economy as well as real-time simulation speed.

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1. Introduction

Rising fuel costs, stringent legal standards and increasing environmental concerns have made car manufacturers produce vehicles with high fuel efficiency and low emissions. This is possible due to new components and technologies that are introduced in automotive powertrains (e.g. turbo charging, exhaust gas recirculation, continuous variable transmission). Unfortunately, it seems that the control software of powertrains remains backward with respect to their complexity [1]. While most current strategies are based on heuristics and look-up tables, [2,3] have shown that model predictive control has a large potential for automotive powertrain control design. One of the most attractive solutions for sustainable transportation to car manufacturers is the hybrid electric powertrain. Hybrid electric vehicles exploit energy production and energy storage systems to achieve improved fuel economy with respect to conventional powertrains. For further improvement in fuel economy and emissions performance, plug-in hybrid electric vehicles (PHEVs) were introduced. These vehicles benefit from a larger power storage system which leads to a longer full-electric range in comparison to HEVs. As such, they can significantly reduce the environmental footprint of the vehicle. These vehicles are one step closer to the full electric vehicle (EV) but more attractive to the market with range-anxiety concerns for EVs.

To maximize fuel economy and emissions performance, control strategies are required to estimate the amount of energy to be produced and stored optimally. HEV power management decides on how much power should be produced by the internal combustion engine and how much should be stored/released from the electric drive to achieve the demanded power at the wheels, while enforcing the operating constraints, and to optimize fuel economy at the same time. The PHEV's larger battery provides more flexibility and on the other hand more complexity for the power management system in comparison to HEVs. Several strategies for HEV/PHEV power management have been proposed, including dynamic programming (DP), stochastic dynamic programming (SDP), equivalent fuel consumption minimization (ECMS), and model predictive control (MPC). To fully exploit these strategies' capability for improving fuel economy and emission performance, complete information of the driving schedule is required beforehand. Unfortunately, information about the future driving cycle is not available during conventional driving. Furthermore, planning for the whole future driving cycle is computationally demanding. Even by having the exact driving schedule available at the starting point, DP cannot be implemented in real time, although it can offer the most efficient solution. As a result, rule-based strategies based on DP results are usually implemented to the powertrain controller.

☆ Fully documented templates are available in the elsarticle package on CTAN.

* Corresponding author.

E-mail address: ataghavi@uwaterloo.ca (A. Taghavipour).

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Stochastic models can reduce some of these problems, but the choice of stochastic model and its identification still faces some challenges [4]. Moura et al. derived an optimal power management scheme for a plug-in hybrid vehicle (power-split architecture) based on stochastic dynamic programming [5]. Musardo et al. [6] proposed an adaptive ECMS (A-ECMS) method based on driving condition, which calculates the equivalency factor in ECMS technique for parallel HEVs. Tulpule et al. [7] used the ECMS approach to design a power management strategy in series and parallel PHEVs by considering two operation modes (EV and Blended).

Model predictive control is another approach for designing a power management strategy. The success of MPC in industrial applications is due to its ability to handle processes with many manipulated and controlled variables and constraints in a rather systematic manner [8]. Furthermore, MPC allows an objective function to be optimized by the controller. Other advantageous MPC features are the capability of dealing with time delays [9], of taking advantage from future information [10], and of rejecting measured and unmeasured disturbances [11]. It is noteworthy that MPC embodies both (receding horizon) optimization and feedback adjustment. Model predictive control has been applied to diesel engines control [12], catalyst control [13], transmission control [14], and HEV [15,16]/PHEV [17,18] power management.

Despite the obvious benefits of MPC, its capabilities are limited due to the computational effort required for solving the online optimization problem of the MPC [19]. In our previous work [20], we compared the performance of A-ECMS strategy to MPC approach for designing a power management strategy for a PHEV. Both strategies improved fuel economy by 10% in comparison to the baseline control strategy, but A-ECMS was approximately 15% faster than MPC.

This shortcoming can be overcome by using the so-called explicit MPC (eMPC) methods. In eMPC the online optimization problem involved in the MPC is solved off-line using multi-parametric programming approaches and the control variables and the value function of the optimization problem are derived as explicit functions of the system state variables, as well as the critical regions of the state-space where these functions are valid. Such a function is piecewise affine in most cases, so that the MPC controller maps into some polyhedral regions that can be stored as a look-up table of linear gains [8]. The key advantage of explicit MPC is that it can replace the online optimization problem of the traditional MPC with a set of function evaluations, significantly reducing the computational effort required for the implementation [19].

Explicit MPC techniques [21] can be used to synthesize the controller as a piecewise affine function. With this approach, the MPC can be implemented in a micro-controller without the need for an optimization solver and satisfying limitations on memory and computational power characteristic of automotive electronic control units (ECUs).

In practice, explicit MPC is limited to relatively small problems (typically 1–2 inputs, up to 5–10 states, up to 3–4 free control moves). But it allows one to reach very high sampling frequencies and requires a very simple control code to be embedded in the system [8].

Industrial problems addressed through explicit MPC techniques have been reported in technical papers, starting from what is probably the first work in this domain which is traction control [22]. Most applications of explicit MPC have been reported in the automotive domain and electrical power converters.

The hardware-in-the-loop (HIL) systems have become efficient tools for strategy and interface software development [23]. The HIL systems allow a lot of control function development to be done and verified ahead of a vehicle build. Improved software quality and early verification of software leads to reduced vehicle commissioning time if a minimum level of functionality exists before being handed off to the various engineering teams for further development [24].

The authors in [25] applied the HIL approach to a parallel HEV configuration in order to analyze fuel reduction benefits due to hybridization without any influence of vehicle characteristics or engine technology improvement. Petersheim and Brennan [26] down-scaled the electric machine and the battery of an HEV to perform a lab-scale HIL simulation.

The advent of microprocessor-based electronic control units (ECUs) for car engines and powertrain created a need for new tools for testing, calibrating, and validating these ECUs. HIL simulation met this need, and became a key technology for engine ECU testing and calibration [27].

Lee et al. present a formal process for developing such a HIL simulator that uses automatic code generation to streamline the transition of control system designs from pure simulation to a commercial embedded code [28].

The use of HIL simulation for automotive ECU development is not limited to engine applications. In fact, HIL simulation has been used effectively for the development, calibration, and validation of transmission and driveline electronic control units.

In this paper, we propose a near-optimal, real-time implementable solution for a PHEV power management strategy using explicit model predictive control. In [4], the authors used an eMPC solution for a series HEV, but to the best of our knowledge, this is the first time that an explicit model predictive controller is designed and implemented for a power-split PHEV architecture. Due to system complexity, there are some challenges for finding an appropriate control-oriented model. Using eMPC is only practical for relatively small problems because the size of the controls database is exponentially increased by the number of state variables. Therefore, the control-oriented model should be very simple, but accurate enough to capture the complex dynamics of a power-split PHEV powertrain. Moreover, the control-oriented model and the optimization cost function should be chosen in such a way that they guarantee a feasible solution, optimality, stability and desirable performance for the controller. The proposed control system is a switched discrete-time one. As a result, stability analysis is required to make sure that the control system keeps its performance for all PHEV operating points. Therefore, we introduce an innovative control-oriented model that is very simple and addresses the mentioned issues.

In the next section, we introduce the simulation model. Then, we discuss the power management strategy design and implementation by developing an appropriate control-oriented model. In Section 4, we show the polytopes resulting from solving the eMPC and discuss the physical interpretation of different regions. Then we discuss the stability of the closed-loop system. In Section 7, we apply the designed controller to the simulation model, which is followed by HIL testing. Finally, we discuss the results and compare them with the MPC approach.

2. Powertrain simulation model

Among the different architectures for a hybrid electric vehicle, the power split configuration seems to be the most efficient for a limited size of battery [29]. In a power split configuration, the engine, the electric motor and the generator are connected to each other by means of 2 planetary gear sets (PGS). Fig. 1 shows the schematic of the Toyota Prius plug-in powertrain. The engine shaft and first electric machine are connected to the carrier and the sun gear of PGS 1. The second electric machine is connected to the sun gear of the second PGS.

To derive the dynamics of the system, it is assumed that the mass of the pinion gears is small, there is no friction, no tire slip

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