
ADVANCED MODEL PREDICTIVE CONTROL

Edited by **Tao ZHENG**

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Advanced Model Predictive Control

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Preface

Since the earliest algorithm of Model Predictive Control was proposed by French engineer Richalet and his colleagues in 1978, the explicit background of industrial application has made MPC develop rapidly. Different from most other control algorithms, the research trajectory of MPC is originated from engineering application and then expanded to theoretical field, while ordinary control algorithms often have applications after sufficient theoretical work.

Nowadays, MPC is not just the name of one or some specific computer control algorithms, but the name of a specific controller design thought, which can derive many kinds of MPC controllers for almost all kinds of systems, linear or nonlinear, continuous or discrete, integrated or distributed. However, the basic characters of MPC can be simply summarized as a model used for prediction, online optimization based on prediction and feedback compensation, while there is no special demand on the form of the system model, the computational tool for online optimization and the form of feedback compensation.

The linear MPC theory is now comparatively mature, so its applications can be found in almost every domain in modern engineering. But robust MPC and nonlinear MPC (NMPC) are still problems for us. Though there are some constructive results because many efforts have been made on them in these years, they will remain the focus of MPC research for a long period in the future.

In the first part of this book, to present recent theoretical developments of MPC, Chapter 1 to Chapter 3 introduce three kinds of Fast Model Predictive Control, and Chapter 4 presents Model Predictive Control for distributed systems. Model Predictive Control for nonlinear systems, multi-variable systems and other special model are proposed in Chapters 5 through 10.

To give the readers successful examples of MPC's recent applications, in the second part of the book, Chapters 11 through 18 introduce some of them, from sugar crystallization process to paper-making system, from linear system to nonlinear system. They can, not only help the readers understand the characteristics of MPC more clearly, but also give them guidance how to use MPC to solve practical problems.

Authors of this book truly want it to be helpful for researchers and students who are concerned about MPC, and further discussions on the contents of this book are warmly welcome.

Finally, thanks to InTech and its officers for their efforts in the process of edition and publication, and thanks to all the people who have made contributes to this book, including our dear family members.

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Part 1

New Theory of Model Predictive Control

Fast Model Predictive Control and its Application to Energy Management of Hybrid Electric Vehicles

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1. Introduction

Modern day automotive engineers are required, among other objectives, to maximize fuel economy and to sustain a reasonably responsive car (i.e. maintain driveability) while still meeting increasingly stringent emission constraints mandated by the government. Towards this end, Hybrid Electric Vehicles (HEVs) have been introduced which typically combine two different sources of power, the traditional internal combustion engine (ICE) with one (or more) electric motors, mainly for optimising fuel efficiency and reducing Carbon Dioxide (CO₂) and greenhouse gases (GHG) (Fuhs, 2008).

Compared to the vehicles with conventional ICE, hybrid propulsion systems are potentially capable of improving fuel efficiency for a number of reasons: they are able to recover some portion of vehicle kinetic energy during braking and use this energy for charging the battery and hence, utilise the electric motor at a later point in time as required. Also, if the torque request (demanded by driver) is below a threshold torque, the ICE can be switched off as well as during vehicle stop for avoiding engine idling. These are in fact merely few representative advantages of the hybrid vehicles compared to those of conventional vehicles. There are also other benefits hybrid electric vehicles could offer in general, e.g. engine downsizing and utilising the electric motor/motors to make up for the lost torque. It turns out that the internal combustion engine of the hybrid electric vehicle can be potentially designed with a smaller size and weight which results in higher fuel efficiency and lower emissions (Steinmaurer & Del Re, 2005).

Hybrid electric vehicles have been received with great enthusiasm and attention in recent years (Anderson & Anderson, 2009). On the other hand, complexity of hybrid powertrain systems have been increased to meet end-user demands and to provide enhancements to fuel efficiency as well as meeting new emission standards (Husain, 2003).

The concept of sharing the requested power between the internal combustion engine and electric motor for traction during vehicle operation is referred to as "vehicle supervisory control" or "vehicle energy management" (Hofman & Druten, 2004). The latter term, employed throughout this chapter, is particularly referred to as a control allocation for delivering the required wheel torque to maximize the average fuel economy and sustain the battery state of charge (SoC) within a desired charging range (Fekri & Assadian, 2011).

The vehicle energy management development is a challenging practical control problem and a significant amount of research has been devoted to this field for full HEVs and Electric Vehicles (EVs) in the last decade (Cundev, 2010). To tackle this challenging problem, there are currently extensive academic and industrial research interests ongoing in the area of hybrid electric vehicles as these vehicles are expected to make considerable contributions to the environmentally conscious requirements in the production vehicle sector in the future – see (Baumann et al., 2000) and other references therein.

In this regard, we shall analysis and extend the study done by (Sciarretta & Guzzella, 2007) on the number of IEEE publications published between 1985 and 2010. Figure 1 depicts the number of publications recorded at the IEEE database¹ whose abstract contains at least one of the strings "hybrid vehicle" or "hybrid vehicles".

From Figure 1, it is obvious that the number of publications in the area of hybrid electric vehicles (HEVs) has been drastically increased during this period, from only 2 papers in 1985 to 552 papers in 2010. Recall that these are only publications of the IEEE database - there are many other publications than those of the IEEE including books, articles, conference papers, theses, filed patents, and technical reports which have not been taken into account in this study. Besides, a linear regression analysis of the IEEE publications shown in Figure 1 indicates that research in the field of hybrid vehicles has been accelerated remarkably since 2003. One may also predict that the number of publications in this area could be increased up to about 1000 articles in 2015, that is nearly twice as many as in 2010 - this is a clear evidence to acknowledge that HEVs research and development is expected to make considerable contributions to both academia and industry of production automotive sector in the future.

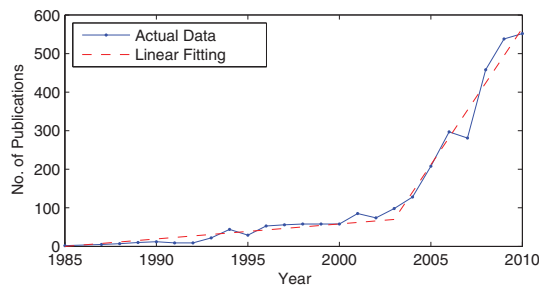


Fig. 1. Hybrid vehicle research trend based on the number of publications of the IEEE over the period 1985 to 2010.

Here are the facts and regulations which must be taken into consideration by automotive engineers:

- Due to the ever increasing stringent regulations on fuel consumption and emissions, there are tremendous mandates on Original Equipment Manufacturers (OEMs) to deliver fuel-efficient less-polluting vehicles at lower costs. Hence, the impact of advanced controls for the application of the hybrid vehicle powertrain controls has become extremely important (Fekri & Assadian, 2011).

¹ See <http://ieeexplore.ieee.org> for more information.

- It is essential to meet end-user demands for increasingly complex new vehicles towards improving vehicle performance and driveability (Cacciatori et al., 2006), while continuing to reduce costs and meeting new emission standards.
- There is a continuous increase in the gap between the theoretical control advancement and the control strategies being applied to the existing production vehicles. This gap is resulting on significant missed opportunities in addressing some fundamental functionalities, e.g. fuel economy, emissions, driveability, unification of control architecture and integration of the Automotive Mechatronics units on-board vehicle. It seems remarkably vital to address how to bridge this gap.
- Combined with ever-increasing computational power, fast online optimisation algorithms are now more affordable to be developed, tested and implemented in the future production vehicles.

There are a number of energy management methods proposed in the literature of hybrid vehicles to minimize fuel consumption and to reduce CO₂ emissions (Johnson et al., 2000). Among these energy management strategies, a number of heuristics techniques, say e.g. using rule-based or Fuzzy logic, have attempted to offer some improvements in the HEV energy efficiency (Cikanek & Bailey, 2002; Schouten et al., 2002) where the optimisation objective is, in a heuristic manner, a function of weighted fuel economy and driveability variables integrated with a performance index, to obtain a desired closed-loop system response. However, such heuristics based energy management approaches suffer from the fact that they guarantee neither an optimal result in real vehicle operational conditions nor a robust performance if system parameters deviate from their nominal operating points. Consequently, other strategies have emerged that are based on optimisation techniques to search for sub-optimal solutions. Most of these control techniques are based on programming concepts (such as linear programming, quadratic programming and dynamic programming) and optimal control concepts, to name but a few (Ramsbottom & Assadian, 2006; Ripaccioli et al., 2009; Sciarretta & Guzzella, 2007). Loosely speaking, these techniques do not offer a feasible casual solution, as the future driving cycle is assumed to be entirely known. Moreover, the required burdensome calculations of these approaches put a high demand on computational resources which prevent them to be implemented on-line in a straightforward manner. Nevertheless, their results could be used as a benchmark for the performance of other strategies, or to derive rules for rule-based strategies for heuristic based energy management of HEVs (Khayyam et al., 2010).

Two new HEV energy management concepts have been recently introduced in the literature. In the first approach, instead of considering one specific driving cycle for calculating an optimal control law, a set of driving cycles is considered resulting in the stochastic optimisation approach. A solution to this approach is calculated off-line and stored in a state-dependent lookup table. Similar approach in this course employs Explicit Model Predictive Control (Beccuti et al., 2007; Pena et al., 2006). In this design methodology, the entire control law is computed offline, where the online controller will be implemented as a lookup table, similar to the stochastic optimisation approach. The lookup table provides a quasi-static control law which is directly applicable to the on-line vehicle implementation. While this method has potential to perform well for systems with fewer states, inputs, constraints, and "sufficiently short" time-horizons (Wang & Boyd, 2008), it cannot be utilised in a wide variety of applications whose dynamics, cost function and/or constraints are time-varying due to e.g.

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