Engineering Applications of Artificial Intelligence 48 (2016) 106–118

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

An ELM based predictive control method for HCCI engines

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ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form
18 October 2015
Accepted 23 October 2015
Available online 21 November 2015

Keywords:
Model predictive control
Extreme Learning Machines
Engine control
HCCI engine
System identification
Neural networks

ABSTRACT

We formulate and develop a control method for homogeneous charge compression ignition (HCCI) engines using model predictive control (MPC) and models learned from operational data. An HCCI engine is a highly efficient but complex combustion system that operates with a high fuel efficiency and reduced emissions compared to the present technology. HCCI control is a nonlinear, multi-input multi-output problem with state and actuator constraints which makes controller design a challenging task. In this paper, we propose an MPC approach where the constraints are elegantly included in the control problem along with optimality in control. We develop the engine models using experimental data so that the complexity and time involved in the modeling process can be reduced. An Extreme Learning Machine (ELM) is used to capture the engine dynamic behavior and is used by the MPC controller to evaluate control actions. We also used a simplified quadratic programming making use of the convexity of the MPC problem so that the algorithm can be implemented on the engine control unit that is limited in memory. The working and effectiveness of the proposed MPC methodology has been analyzed in simulation using a nonlinear HCCI engine model. The controller tracks several reference signals taking into account the constraints defined by HCCI states, actuators and operational limits.

1. Introduction

In recent years, the requirements on automotive performance, emissions and cost have become increasingly stringent. As a consequence, the auto industry has been continuously introducing advanced technology to meet these demands (EPA, 2012). Invariably, such systems introduce additional complexity and associated challenges in design and operation. Homogeneous charge compression ignition (HCCI) is an advanced combustion technology integrating several of the recent automotive advancements including variable valve timing, exhaust gas recirculation (EGR), intake charge boosting, etc. (EPA, 2012). Although HCCI engines are very efficient combustion systems, they also pose several challenges when it comes to practically using it for automobiles. Some of them include the absence of a direct control over combustion, having a narrow operating region and high sensitivity to ambient conditions. Control of HCCI combustion is a challenging problem and a model based approach is typically employed (Bengtsson et al., 2006a; Ravi et al., 2010), where a control-oriented model developed using first principles is used. Although physics based models are the only choice before and during the engine design stage for making design decisions, such models usually require expert knowledge and take a long time to develop. However when a matured prototype is available, controller development needs to be accelerated. To this end, we propose to use data-based predictive models that can be developed fairly quickly without much expert knowledge.

The HCCI engine is equipped with sensors such as manifold temperature and pressure sensors, in-cylinder pressure transducers that can provide valuable data about the engine's behavior. We can draw insights about the general combustion behavior of the engine including efficiency, emissions and combustion stability using the in-cylinder pressure measurements. We have shown in our prior work that in-cylinder pressure data can be used to develop control oriented models of the engine's state variables and operating envelope using neural networks (Janakiraman et al., 2013) and support vector machines (Janakiraman et al., 2014, 2015). In this paper, we show how to use these models to develop an optimal controller for the HCCI engine.

For the HCCI modeling problem, Extreme Learning Machines (ELMs) (Huang et al., 2006) were selected for their fast operation and their extraordinary approximation capabilities to fit nonlinear systems. ELM techniques have been applied successfully to engine fault detection (Yin et al., 2014; Wong et al., 2015b) and modeling diesel and biodiesel engines using data (Wong et al., 2013, 2015a;

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http://dx.doi.org/10.1016/j.engappai.2015.10.007
0952-1976/

Mozaffari and Azad, 2014) showing its suitability in modeling combustion engines. Furthermore, ELM models have been recursively applied for automotive control purposes where control algorithms using ELM have been developed for engine cold start emission control (Azad et al., 2015), air-ratio control (Wong et al., 2014) and autonomous cruise control of electric vehicles (Mozaffari et al., 2015). The major advantage of ELM (and data based modeling in general) is that it approximates the real system and makes no (or minimal) simplifying assumptions about the underlying system. The dynamics of sensors, actuators and other complex processes, which are usually overlooked/hard to model using first principles, can be captured using the identification method. In addition, for a system like the combustion engine, prototype hardware is typically available and extensive experimental data can be collected making the data based approach more suitable. Data based identification is less common for HCCI engines owing to its nonlinear, highly sensitive and unstable behavior. However, we have shown in our prior work that neural networks (Janakiraman et al., 2013) and support vector machines (Janakiraman et al., 2014) are indeed suited for accurately predicting the dynamics of HCCI. Neural network models (based on backpropagation) have issues with local minima while support vector machines result in memory intensive models making them unsuitable for real engine implementations (Janakiraman et al., 2014). ELMs on the other hand solve a convex optimization problem resulting in a global optimal solution and are simple enough to be implemented onboard the engine control unit (ECU), which makes it a good candidate for the problem considered in this work.

As our model is a black-box, we propose to use a model predictive control (MPC) approach for the HCCI control problem because MPC can efficiently handle black-box type models for evaluating control candidates (Maciej, 2009). In addition, MPC is well suited for handling operation related and hardware related constraints in an elegant manner. Even for simple linear systems, MPC has been shown to outperform traditional control such as PID (Maciejowski, 2002) and LQ control (Franko et al., 2011; Bengtsson et al., 2006b). In general terms, MPC makes use of a mathematical model of the system and solves an optimization problem with the given constraints to achieve an optimal control solution (Maciejowski, 2002). In this paper, an ELM engine model is used to make predictions which are then used by the MPC module to make control decisions for tracking a given reference command. Model predictive control is quite popular in the automotive domain for both spark ignited (Re et al., 2010) and compression ignited engines (Ortner et al., 2006; Ortner and Del Re, 2007). However, the application of MPC to HCCI engines is at an early stage involving physics based models (Widd et al., 2014; Li and Wang, 2013) and simple identification models (Bengtsson et al., 2006a). This paper advances the MPC application to HCCI engines by demonstrating it on a data based non-linear model that could capture more complex behavior of the engine for a wide range of operation. Further, by using concepts from convex optimization, the MPC is converted into a quadratic programming problem and solved using minimum overhead suitable for implementing onboard the engine ECU. Thus the main contribution of this paper is an integrated control framework that applies existing ideas from ELM, predictive control and convex optimization to a complex combustion engine. This includes optimal model selection (tuning model hyper-parameters), training and validation of the model to the HCCI engine data, linearizing the ELM model considering the structure of ELMs, and a simplified quadratic program update developed for the HCCI system suitable for real-time application.

As there are several components involved, a road-map of our methodology is shown in Fig. 1. Real experimental data from a prototype HCCI engine is taken offline and used to train ELM models. A supervised batch learning algorithm is used to train the ELM models and the model is validated for generalization performance using real engine test data. The ELM models act as a proxy to the actual engine where candidate control trajectories are evaluated by the MPC controller. The evaluation is done by solving an optimization problem that has a well defined cost function with constraints. The MPC controller is required to provide an optimal control solution at every sampling interval of the engine. We make use of model linearization and the convexity of the MPC problem

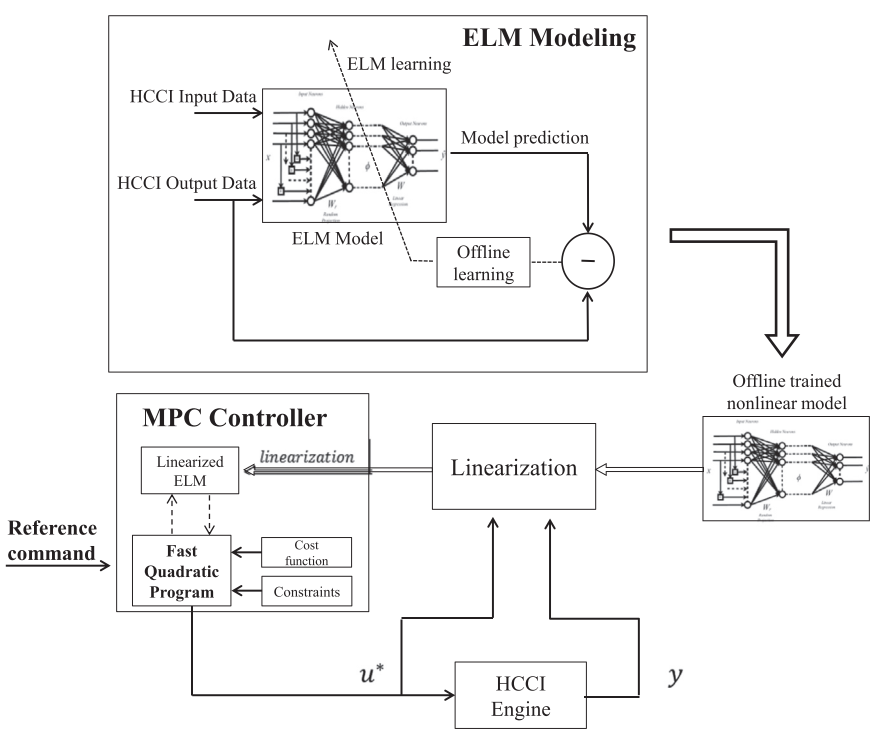

Fig. 1. An integrated control framework for HCCI combustion control showing the use of ELM based engine models and model predictive controller using a fast quadratic programming solver.