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Nonlinear model predictive controller design based on learning model for turbocharged gasoline engine of passenger vehicle ☆

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ABSTRACT

In this paper, a neural-network-based nonlinear model predictive control (NMPC) scheme is investigated to realize coordinated control over the throttle and wastegate of a turbocharged gasoline engine of a passenger vehicle. First, due to the presence of MAPs and the complex structure of the turbocharged engine, establishing a mechanism model for controller design is very complicated. Benefiting from a large amount of experimental data, a predictive model is learned by a neural network to predict the future dynamics of the engine air-path system, and the accuracy of this model is verified. Second, to address the system constraints and coupling, a nonlinear model predictive controller is proposed to track the desired intake manifold pressure and boost pressure for meeting the engine torque demand. Third, quantum-behaved particle swarm optimization (QPSO) is applied for optimization of the NMPC objective function to obtain a more accurate solution. Finally, the performance of the control system is tested using the commercial simulation software AMESim.

1. Introduction

In recent decades, the focus for gasoline engines generally used in passenger vehicles has been on the requirements of reducing pollutant emissions and improving fuel consumption while improving dynamic quality and drivability. These requirements could be achieved with the attractive strategy called turbocharger technology [1,2]. A turbocharger recycles the energy of exhaust gas to increase the amount of air entering cylinders, to achieve these goals.

Based on the torque-centered engine control scheme, the driver's torque demand is converted into tracking control of the intake manifold pressure and boost pressure in the turbocharged gasoline engine [3]. Then, the tracking control of the intake manifold pressure and boost pressure is used as the control target of the turbocharged gasoline engine air-path system, and the throttle position and wastegate position are used as control inputs. The addition of a complex turbocharger introduces strong nonlinearity, coupling and a large number of MAPs (lookup tables) into the turbocharged engine [4]. Moreover, actuator saturation is a characteristic of the throttle and wastegate. Hence, the control problem of a turbocharged gasoline engine air-path system could be described as a two-input-two-output (TITO) optimal control problem with the characteristics of

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strong nonlinearity, coupling and constraints. Traditionally, the most commonly used controller for engine air-path systems is the proportional-integral-derivative (PID) controller [5,6], which often produces overshoot and poor tracking performance. Therefore, an advanced model-based control is necessary to improve the turbocharged engine control performance. Currently, many researchers are focusing on the control scheme for turbocharged engine air-path systems, and most of them are based on the mechanism model. The control scheme can fall into two categories. The first category is to ignore the coupling between the intake system and exhaust system and convert it into a single-input-single-output (SISO) control problem. This method only considers the tracking control of boost pressure using the wastegate and the throttle is taken as an external disturbance. A linear neural predictive controller for tracking boost pressure was proposed in [7]. A control strategy based on constrained motion planning and feedback linearization was developed in [8]. A composite adaptive internal model control (CAIMC) based on a first-order linear model was proposed for the wastegate in [9]. A nonlinear internal model controller was designed for wastegate control to track desired boost pressure in [10]. Although the aforementioned methods are easy to realize, the control performance could be degraded by the correlative controllers that control the throttle to track the intake manifold pressure, particularly under rapid throttle adjustment. The second category is the coupling control of the intake system and exhaust system. A linear model predictive control (MPC) to track the air mass flow entering cylinders and boost pressure by coordinated controlling the throttle and wastegate coordinately was developed in [11]. A nonlinear MPC (NMPC) was proposed in [12] to adjust the throttle and wastegate to track the intake manifold pressure, where the boost pressure is not considered. Overall, compared with other control algorithms, MPC can address multiple-input-multiple-output (MIMO), nonlinearity, coupling and constraint problems naturally [13–15], thus making it suitable for the controller design of the turbocharged gasoline engine air-path system.

To apply NMPC to the turbocharged gasoline engine air-path system, the following problems have to be resolved:

(1) A high-precision and simple predictive model is needed, and the state variables should be measurable for engineering realization convenience [16]. The mechanism modeling of turbocharged gasoline engines is very complex and contains MAPs, thus making it not suitable for predicting the system dynamics for MPC. Recently, neural networks have become one of the most popular approaches for identifying nonlinear systems [17,18]. In addition, the learning model can be learned directly from the measurable input-output data.
(2) An accurate and fast solution algorithm for nonlinear constrained optimization is required. Most of the traditional optimization methods are based on the local gradient iterative algorithm, and such methods are generally suitable for convex and simple nonlinear optimization. Recently, evolutionary algorithms have become effective methods for solving this problem. In particular, particle swarm optimization (PSO) is appropriate for this problem because of its simple theory and parallel computation [19]. However, the standard PSO (SPSO) can easily fall into premature convergence. Thus, a novel PSO should be applied to solve the optimization problem for NMPC.

Based on the above questions, the contributions of this paper can be summarized as follows:

- A nonlinear predictive model for a turbocharged engine air-path system is learned by a neural network, which is more suitable for the controller design. In addition, the method only has two measurable state variables, which can reduce the computational burden and enable direct use in engineering.
- A nonlinear model predictive controller is designed to realize coordinated control of the throttle and wastegate for turbocharged engine air-path systems. The tracking problems of the intake manifold pressure and boost pressure are considered in the objective function, and the mechanical limitations of the throttle and wastegate are considered as input constraints.
- A novel optimization method is developed to optimize the objective function of the NMPC. This method can solve the constrained optimization problems accurately and quickly.

The remainder of this paper is organized as follows. Section 2presents the learning process of the neural network for turbocharged gasoline engines and verifies the feasibility of the predictive model. Section 3proposes a detailed design of NMPC for turbocharged engines. Section 4introduces the optimization solution and analyzes its performance for the implementation of NMPC. Section 5 presents the simulation results. Section 6 draws the conclusion of this paper.

2. Neural network predictive model

2.1. Description of turbocharged engine and motivation

A schematic diagram of a turbocharged gasoline engine is depicted in Fig. 1. The intake and exhaust ports of this gasoline engine are connected by the turbocharger. A throttle is placed in front of the intake manifold to adjust the amount of air entering the cylinders, and an electric wastegate is placed in the turbine bypass path to adjust the turbine rotation speed. A detailed introduction to turbocharged gasoline engines was presented in [20].

For turbocharged gasoline engines, the mechanism model is primarily adopted in the traditional modeling method. A typical mechanism model of a turbocharged engine is given as follows [10,21]: