Transportation Research Part C 69 (2016) 60–78

Contents lists available at ScienceDirect

Transportation Research Part C

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

Online distributed cooperative model predictive control of energy-saving trajectory planning for multiple high-speed train movements

Xihui Yan [a,b], Baigen Cai [a,b], Bin Ning [a], Wei ShangGuan [a,b,*]

[a] State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China
[b] Beijing Engineering Research Center of EMC and GNSS Technology for Rail Transportation, Beijing Jiaotong University, Beijing 100044, China

ARTICLE INFO

Article history:
Received 15 November 2015
Received in revised form 19 May 2016
Accepted 26 May 2016
Available online 1 June 2016

Keywords:
High-speed train
Energy-saving
Trajectory planning
Model predictive control
Ant colony optimization

ABSTRACT

The cooperative energy-efficient trajectory planning for multiple high-speed train movements is considered in this paper. We model all the high-speed trains as the agents that can communicate with others and propose a local trajectory planning control model using the Model Predictive Control (MPC) theory. After that we design an online distributed cooperative optimization algorithm for multiple train trajectories planning, under which each train agent can regulate the trajectory planning procedure to save energy using redundancy trip time through tuning ACO's heuristic information parameter. Compared to the existing literature, the vital distinctions of our work lies not only on the online cooperative trajectory planning but also on the distributed mechanism for multiple high-speed trains. Experimental studies are given to illustrate the effectiveness of the proposed methods with the practical operational data of Wuhan-Guangzhou High-speed Railway in China.

1. Introduction

In order to satisfy the great demand for transport capacity produced by the public society, the high-speed railway system has been developing to provide the safest and most cost-effective passenger service in recent years. With the rapid development of high-speed railway, more and more railway lines will be put into operation in China (Sun et al., 2014). To make a safe and efficient driving, the high-speed train driver should operate the train referring to a preplanned speed commands which are generated from a set of alternative train-speed trajectories per inter-station with different running times. The reference train-speed trajectory, which determines the authorized speed in a preset position and operational time, plays a very important role in ensuring the high-speed train functions optimally and has a great influence on the driving performance including punctuality, energy consumption and jerk, etc.

Train-speed trajectory optimization is essentially a multiple variable optimization problem. Ishikawa (1968) firstly applied Pontragin's principle to solve the train optimal control problem in the 1960s. Later on, more and more researchers were focus on this optimal control problem by using analytical solution or numerical optimization methods. Albrecht et al. gave a detailed introduction for optimal train control, they discuss the problem of finding an energy-efficient driving strategy for a train journey on an undulating track with steep grades subject to a maximum prescribed journey time (Albrecht et al., 2015a,b). Besides, for the analytical approach, there are two kinds of solutions according to whether the output force is con-

* Corresponding author at: State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China.
E-mail addresses: xihuiyan@bjtu.edu.cn (X. Yan), bgcai@bjtu.edu.cn (B. Cai), bning@bjtu.edu.cn (B. Ning), wshg@bjtu.edu.cn (W. ShangGuan).

http://dx.doi.org/10.1016/j.trc.2016.05.019
0968-090X/

tinuous or discrete. A systematic research on discrete output force based optimal train trajectory planning problem was given by the Scheduling and Control Group at the University of South Australia (Howlett and Pudney, 1995; Howlett and Leizarowitz, 2001). For the continuous problem, Milroy (1980) firstly formulated the minimization problem of mechanical energy consumption for train operation, who showed that an energy-efficient speed trajectory for short trip has three phases including maximum acceleration, coasting and maximum braking. Then, Howlett (1990) furthermore provided the first theoretical confirmation that an optimal train trajectory should use a maximum acceleration–cruising–coasting–maximum braking condition sequence. By considering the variable gradient, Golovitcher (1996) proved that the cruising condition must be interrupted by a traction condition for each steep uphill and by a coasting condition for each steep downhill. Khmelnitsky (2000) presented a comprehensive study on train energy-efficient trajectory planning problem, in which variable gradient, variable traction efficiency and speed limit were all considered.

Besides the analytical approach, the numerical optimization method also has been widely applied in train trajectory planning problem due to the high computing power of the on-board computer. Many advanced techniques, such as fuzzy algorithm (Li et al., 2011; Chang et al., 1999), meta-heuristic algorithms (Ciccarelli et al., 2012; Shangguan et al., 2015; Ke et al., 2009; Wong and Ho, 2004; Yang et al., 2014, 2013) and dynamic programming (Ko et al., 2004; Xu et al., 2014) have been applied to solve the train trajectory planning problem. Lu et al. (2013) proposed a distance-based train trajectory searching model, where three optimization algorithms, i.e., the ant colony optimization (ACO) algorithm, the genetic algorithm and dynamic programming, were applied to search for the optimum train speed trajectory. Wang et al. (2013) studied the optimal trajectory planning problem for train operations under constraints and fixed arrival time using the pseudospectral method and the mixed-integer linear programming technology respectively. Chevrier (2010) developed a state-of-the-art evolutionary algorithm with Pareto approach to perform a speed-based model, building speed profiles in a multi-objective way according to a set of predefined rules, the state-of-the-art evolutionary algorithm was also applied by Lejeune et al. (2012) to optimize journey duration and energy consumption.

All above researches were mainly focus on single train operation control. However, for the modern railway systems, train operation control approach has been changed due to the application of moving block system technology. Under the moving block system, the distances between two trains are continuously adjusted according to their actual speeds and positions. Goverde et al. (2013) studied railway line capacity problem of different railway signaling systems under scheduled and disturbed conditions. D'Ariano et al. solved real-time timetable perturbations problem using conflict resolution and train speed coordination approaches (D'Ariano et al., 2007; D'Ariano and Albrecht, 2006). Ning et al. (2015) proposed an integrated control method to optimize train headway by adjusting the train arrival time at stations. The adjustment of train arrival time was achieved using an analytical method, and the speed profile for each train was calculated through a suboptimal method. Li et al. designed a coordinated cruise control strategy for multiple high-speed trains' movement by using the potential fields and LaSalles invariance principle (Li et al., 2015, 2014). Li and Hong (2014a) proposed an integrated energy-efficient operation model to jointly optimize the timetable and speed profile aiming at reducing the tractive energy consumption and improving the utilization of regenerative energy, they also investigated the dynamic train scheduling and control problem for metro rail operations according to changeable passenger demands (Li and Hong, 2014b). Chang et al. (2000) developed a multi-objective programming model for the optimal allocation of passenger train services on an intercity high-speed rail line without branches, they applied the fuzzy mathematical programming approach to determine the train stop-schedule plan, service frequency, and feet size to minimize the operator's total operating cost and the passenger's total travel time loss. Su et al. (2014) analyzed the hierarchy of energy-efficient train operation in subway system and proposed an integrated algorithm to generate the globally optimal operation schedule, which performs better on energy-saving. Goverde et al. (2016) proposed a three-level framework for performance-based railway timetabling and Nikola et al. (2016) developed an integrated micro–macro approach to robust railway timetabling.

Although a number of early research efforts that have attempted to improve the driving performance through trajectory planning, few of them devote to the dynamic trajectory planning problem for multiple train movements. Actually, if the timetable has been regulated, the referred trajectory obtained off-line is however less adapted to the real-time train operation control. In this paper, we investigate the issue of distributed cooperative trajectory planning for multiple high-speed train movements based on our previous works (Yan et al., 2015). We construct a dynamic control scheme for cooperative multiple high-speed trains' trajectory planning using model predictive control theory, which has also been applied to achieve the control of urban traffic networks (Oliveira and Camponogara, 2010; Lin et al., 2012). The proposed approach aims at decreasing the total energy consumption while ensuring the punctuality of all trains, meanwhile to improve the riding comfort. The main contribution of this paper lies on the development of a distributed cooperative trajectory planning strategy for multiple high-speed train movements that exploit MPC based moving horizon optimization and adaptive control conception. The distinct features of the proposed approach are:

- The trains are modeled as agents that can communicate with all the others and each of them has an independently trajectory planning controller. These train agents exchange their trajectory planning results and make a negotiation to determine their own trajectory at each sampling time therefore to handle the cooperative relations under different conditions.
- All the trajectory planning controllers adjust their cooperation parameters according to real-time state and the cooperative relations with other trains, this helps a safe operation for the train group and achieves the cooperation objectives.