Journal of Process Control 55 (2017) 10–29

Contents lists available at ScienceDirect

Journal of Process Control

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

Constrained data-driven optimal iterative learning control

Ronghu Chi [a,*], Xiaohe Liu [a], Ruikun Zhang [b], Zhongsheng Hou [c], Biao Huang [d]

[a] School of Automation & Electronics Engineering, Qingdao University of Science & Technology, Qingdao 266042, PR China
[b] School of Mathematics and Physics, Qingdao University of Science and Technology, Qingdao 266042, PR China
[c] Advanced Control Systems Lab, School of Electronics & Information Engineering, Beijing Jiaotong University, Beijing 100044, PR China
[d] Department of Chemical and Materials Engineering, University of Alberta, Edmonton, AB T6G 2G6, Canada

ARTICLE INFO

Article history:
Received 9 April 2016
Received in revised form 3 February 2017
Accepted 9 March 2017
Available online 10 May 2017

Keywords:
Data-driven control
Iterative learning control
Constrained nonlinear systems
Quadratic programming
Point-to-point tracking tasks

ABSTRACT

A constrained optimal ILC for a class of nonlinear and non-affine systems, without requiring any explicit model information except for the input and output data, is proposed in this work. In order to address the nonlinearities, an iterative dynamic linearization method without omitting any information of the original plant is introduced in the iteration direction. The derived linearized data model is equivalent to the original nonlinear system and reflects the real-time dynamics of the controlled plant, rather than a static approximate model. By transferring all the constraints on the system output, control input, and the change rate of input signals into a linear matrix inequality, a novel constrained data-driven optimal ILC is developed by minimizing a predesigned objective function. The optimal learning gain is unfixed and updated iteratively according to the input and output measurements, which enhances the flexibility regarding modifications and expansions of the controlled plant. The results are further extended to the point-to-point control tasks where the exact tracking performance is required only at certain points and a constrained data-driven optimal point-to-point ILC is proposed by only utilizing the error measurements at the specified points only.

1. Introduction

Iterative learning control (ILC) [1–3] was proposed for repetitive control tasks on a finite time interval. The basic methodology of ILC is to use the prior knowledge of a repetitive process from previous operations to progressively improve tracking performance from iteration to iteration. It has been proved effective for perfect tracking and has achieved a great success in both theory and applications.

In real process industries, a soft limiter is often added directly into the controller to prevent overly large control input signals [4]. However, such a limiter makes the control systems highly nonlinear and may introduce instability. It is also worth pointing out that the input saturation will bring more serious influence on ILC systems because ILC is virtually an integral action along the iteration direction [5]. Recently, several ILC schemes with input saturation have been proposed under the framework of contraction mapping [6–9]. However, the contraction mapping based ILC may cause some poor transient performance, even divergence at some time instants. Therefore, an adaptive ILC with input saturation has been proposed in [5] by introducing a composite energy function. In [10], a “reference governor” based ILC was proposed for input constraint systems. By using RG, the reference signal can be re-designed such that the tracking objective is realizable. The authors in [11] proposed a unified design framework of ILC to deal with nonlinear input uncertainties including input saturations.

Besides the input saturation, the output constraints should also be of a greater concern from a practical viewpoint. For example, the train operation system is constrained not only by the input force because of its mechanical features, but also by its operation speed because of its overspeed limits. The latter seems more important to ensure operation performance and safety. Generally, the position and/or speed is required to be constrained in most motion systems.

In the expository overview of ILC [12], optimal ILC [13–16] is revisited and classified as a connection between ILC and optimal control. By using a predesigned objective function, various practical issues such as constraints on the system output and control input, distur-

* Corresponding author.
E-mail addresses: ronghu_chi@hotmail.com (R. Chi), rkzhang@qust.edu.cn (R. Zhang), zhshhou@bjtu.edu.cn, shtjin@bjtu.edu.cn (Z. Hou), bhuang@ualberta.ca (B. Huang).

http://dx.doi.org/10.1016/j.jprocont.2017.03.003
0959-1524/

bances, measurement noises, and model errors can be considered in a rigorous and systematic manner. Recently, some model predictive control (MPC) based ILC schemes were also proposed in the literatures [17–21] by incorporating the input and output constraints into the optimization problem. For example, in [21], a two-stage algorithm has been devised by modifying and combining the existing Q-ILC and BMPC techniques. Further, based on a 2D piecewise linear description of a batch process, the authors in [22] proposed a constrained ILC approach by solving a linear matrix inequality for performance optimization. However, the main limitation is the requirement of an exact linear model of the controlled plant to guarantee a satisfactory control performance. In order to obtain a linear model for the nonlinear system, two open-loop tests have to be carried out where the difference between the two inputs is kept constant throughout the batch.

To handle broader system nonlinearities and uncertainties, adaptive ILC [23–26] was proposed by exploiting the use of energy function approaches. Consequently, adaptive ILC with state constraints was discussed in [27] by using barrier composite energy function. An adaptive ILC was presented in [28] for output-constrained systems with both parametric and nonparametric uncertainties by introducing a new barrier composite energy function. But, the model structure of the controlled system must be available as a priori knowledge.

In real world applications, however, the model-based control approaches may encounter many challenges with unsatisfactory performance because it is increasingly difficult to gain an exact model of a complex process with increasing scale and complexity. Even if a mathematical model is obtained by first-principles or identification techniques, such a system is not linear in general and the unmodeled uncertainties inevitably exist, which would lead to a poor robustness and lower reliability of the control system. Thus, it is desired to develop a control method less dependent on an explicite model, which is the motivation of data-driven control: the controllers design uses only the input and output measurement data of a plant and the controller itself does not contain any explicite model information of the plant [29–32].

Recently, a data-driven constrained norm-optimal iterative learning control framework for linear time-invariant systems is proposed in [33], where the system's impulse response is estimated using input and output measurements from previous iterations. However, the control performance mainly depends on the estimation precision of the impulse response. To guarantee the estimate values to be equal to the true ones exactly, it is required that the control plant is LTI and no measurement noise or other disturbances are present. More recently, a data-driven terminal ILC [34] is proposed for a special repetitive industrial process where the system input is constant at all sampling instants in a same batch and all the output measurements are not measurable except for the terminal output only. As a consequence, a unified data-driven optimal design framework for generalized iterative learning control [35] is proposed for three control tasks, namely complete trajectory tracking, multiple intermediate points tracking, and single terminal point tracking, respectively. However, the problems of system constraints have not been addressed in the literatures [34,35].

Motivated by the above discussion, in this work we consider the input and output constraints and propose a constrained data-driven optimal iterative learning control (constrained-DDOILC) for a class of nonlinear systems directly. Before proceeding to the controller design, an iterative dynamical linearization method is revisited with supervector formulation such that the nonlinear plant can be transferred into a linear output function with respect to control inputs and the initial states. This linearization is completely equivalent to the original nonlinear process without neglecting any higher order term and in theory the problem of unmodeled uncertainties do not exist consequently. The parameters in the obtained iterative dynamic linear data model do not have special physical meaning and can be updated iteratively according to the input and output measurements only.

Similar to the Q-ILC schemes, an objective function of control input is designed with a penalty term on the iterative input change. The constraints on the bound of control input and the bound of system output, as well as the change rate of the control input across iterations, are transferred into a linear matrix inequality. Then, the constrained-DDOILC law is obtained by minimizing the designed objective function under this LMI condition. Different from the Q-ILC, the proposed constrained-DDOILC is a data-driven control approach, where no explicit mathematical model, either obtained by first-principles or by identification techniques, is needed. The optimal learning gain of the constrained-DDOILC can be iteratively estimated using the real-time input and output data obtained from the system operation, rather than being fixed as that in the Q-ILCs, which makes the proposed constrained-DDOILC more flexible for the modifications or expansions of the controlled plant.

In many practical applications, the objective is to repeatedly track a motion profile in which the tracking errors are of concern only at certain points, instead of every point along the trajectory. For such a control scenario, if removing the unnecessary constraints on the free points other than the specified necessary ones that the plant has to follow, some additional control performance, such as the reduced computation effort and faster convergent speed, could be expected [35]. Several point-to-point ILC (PTP-ILC) approaches have been proposed by using the error information at the given points only [35–38], where, however, the problems of input and output constraints are not well discussed except for [38]. Moreover, most of them are model-based [36–38].

Therefore, this work also extends the proposed constrained-DDOILC to point-to-point motion systems for tracking multiple intermediate points. And a constrained data-driven optimal point-to-point ILC (constrained-DDOPTPILC) is proposed by only utilizing the error measurements at the specified points. Rigorous analysis shows that both of the proposed approaches can achieve a monotonic convergence along the iteration axis. Simulation results are further provided to verify the effectiveness of the proposed constrained-DDOILC and Constrained-DDOPTPILC.

This paper significantly extends the previous work [35]. It improves the design of the DDOILC and DDOPTPILC algorithms by considering the constraints commonly existed in the industrial processes such that the proposed method is always applicable to constrained input and output. The comparative results in the following simulation section also show the significance of this extension since a better control performance can be obtained by the proposed constrained methods. This work is also a significant improvement of traditional Q-ILC for widely existed nonlinear applications, where the control performance is free from the assumption of the linear model, and no linear approximation model is required when applying the proposed constrained methods into nonlinear plants.

The rest of this paper is organized as follows. Section 2 reviews the iterative dynamical linearization and the transfer of the constraints. Section 3 proposes a constrained-DDOILC to track a desired finite trajectory with detail convergence analysis. Section 4 extends the results to the problem of tracking some specified multiple intermediate pass points rather than all the points. Three simulations are given in Section 5 to verify the effectiveness of the proposed approaches. Conclusions are given in Section 6.