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Adaptive preview control for piecewise discrete-time systems using multiple models

Di Wang[a,b], Fucheng Liao[a,*], Masayoshi Tomizuka[c]

[a] School of Mathematics and Physics, University of Science and Technology Beijing, China
[b] School of Automation, Beijing University of Posts and Telecommunications, China
[c] Department of Mechanical Engineering, University of California, Berkeley, USA

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ABSTRACT

In this paper, the problem of multi-model adaptive preview control is proposed for discrete-time systems with unknown piecewise constant coefficients. Following preview control theory, corresponding augmented error systems for piecewise discrete-time systems are constructed. By making use of the Heine–Borel covering theorem, a finite set of fixed augmented systems covering the range of the unknown parameters is established, and associated fixed preview controllers are derived. Based on the core idea of multi-model adaptive control, switching law of the controllers is designed, and eventually, an adaptive preview controller is obtained. The exponential asymptotic stability of closed-loop systems with large uncertainties is discussed in detail. Finally, simulation results are given to demonstrate the effectiveness of the theoretical results.

1. Introduction

Preview control is an extended feedforward control that can improve system performance by utilizing known future knowledge of references and disturbances. Over the past 50 years, preview control theory has received considerable attention and has proved to be a fruitful area of research. As shown in [1–4], optimal preview control for linear systems has been well studied. The problem of preview control has been extended via further research. In [5–9], H_∞ and H_2 criteria were introduced into preview control, and robust optimal preview control for linear and nonlinear systems has been discussed. The authors in [10–12] investigated optimal preview control for systems with multiple sampling rates by using the discrete-time lifting technique. In [13–15], optimal preview control for linear time-variant systems was considered. In recent years, based on descriptor system theory, researchers have considered some descriptor causal systems and designed an optimal controller with preview compensator [16–18].

Successful applications have been made to fields such as vehicle suspension [19–20], X-Y table motion control [21], automated driving [22], brushless DC motors [23], robot control [24,25], and dual-stage actuators [26,27]. The effectiveness of preview control in wind turbine control has also been demonstrated [28–30].

Nevertheless, preview control is model-based control, and its effectiveness deteriorates as the model accuracy goes down. Conventional robust preview control, which has been studied in [5–9], is restricted to small ranges of variations. In fact, dy-

* Corresponding author. Tel.: +8613661395480; fax: +861062334706.
E-mail addresses: diwang@bupt.edu.cn (D. Wang), fcliao@ustb.edu.cn (F. Liao), tomizuka@berkeley.edu (M. Tomizuka).

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namic systems often have large uncertainties due to failures in the system or the presence of large external disturbances. So an adaptation may be naturally introduced: adaptive preview control. In [31–33], multi-model adaptive control using multiple models to identify the unknown plant is considered; as higher level adaptive control, this improves the transient response of control systems with large uncertainties in a stable fashion. The authors in [31] designed a piecewise linear time-invariant switching control law, which leads to a guarantee of Lyapunov stability with an exponential rate of convergence for the state. Based on the method, a kind of switching controller for discrete time system was proposed [32]. In [33], a localization-based method was introduced, which is manifested as the rapid convergence of the switching controller. Ref. [34] promoted the results and discussed the problem of optimal localization. Other several methods of adaptive control based on multiple models were examined in [35].

Currently, the state of research still does not involve taking this adaptive control strategy and using multiple models to construct the preview controller for systems with large uncertainties.

For discrete-time systems with unknown piecewise constant coefficients, the main contribution of this paper is that the designation of adaptive preview controller via sufficient utilization of the known future information of the references. Due to the appearance of large uncertainties on coefficients of the systems, uncertainties became the main roadblock in applying the method of augmented error systems in classical preview control. We make use of a finite set of fixed models to cover the range of unknown parameters, and then design the preview controllers separately for each model. By defining monitoring function and switching principle similarly to [31], the problem is formally converted into a normal optimal control problem that includes preview information. The preview control controller for systems with large uncertainties can be finally obtained in this way, and adaptive preview control theory using multiple models can be established.

Notation: Throughout this paper, $\lambda(A)$ represents an arbitrary eigenvalue of Matrix A. Λ and I denote diagonal matrix and unit matrix, respectively. $\|x\|$ denotes the Euclidean norm $\|x\| = \sqrt{x^T x}$, where $x = (x_1 \quad x_2 \quad \cdots \quad x_m)^T$ is a column vector and T denotes the transposition. The notation $A > 0 (A < 0)$ means A is positive definite (negative definite).

2. Problem statement

Consider the following discrete-time system with unknown piecewise constant coefficients:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) \end{cases}, \tag{1}$$

where $x(k) \in R^n$, $u(k) \in R^r$, $y(k) \in R^m$ represent the state vector, the control input vector, and the output vector, respectively. $x(k)$ is assumed to be accessible. A, B, C are piecewise constant matrices with unknown parameters and appropriate dimensions. The unknown piecewise constant coefficients of system (1) can be fixed by triple $\sigma = (A, B, C)$, so $\sigma = (A, B, C)$ is defined to represent the system. Basic assumptions about system (1) are proposed in the following:

A1: The preview length of the reference signal is M_R, that is, the future values of reference signal $R(k+1)$, $R(k+2)$, ..., $R(k+M_R)$ are available, and the values are assumed not to change beyond the $k+M_R$, namely $R(k+j) = R(k+M_R)$, $j = M_R+1, M_R+2, \cdots$.

A2: The range of unknown parameters for the triple $\sigma = (A, B, C)$ is compact set Σ, and piecewise constant coefficients of system (1) have finite jumps.

A3: For every possible $\sigma = (A, B, C) \in \sum$, (A, B) is stabilizable, $\begin{pmatrix} A-I & B \\ C & 0 \end{pmatrix}$ have full row rank, and (C, A) is detectable. [10]

Remark 1. Condition A2 guarantees that the range of unknown parameters is bounded. For any fixed triple $\sigma_* = (A_*, B_*, C_*) \in \sum$(with known parameters), conditions A1 and A3 guarantee that there exists a preview controller u_{σ_*}, such that closed-loop system of (1) is asymptotically stable. [10]

Define the tracking error as

$$e(k) = R(k) - y(k). \tag{2}$$

In order to design the optimal preview control law for $\sigma_* = (A_*, B_*, C_*) \in \sum$, we introduce the quadratic performance index,

$$J_\beta = \sum_{k=0}^{\infty} \left(e^{2\beta k} \left(e^T(k) Q_e e(k) + \Delta u^T(k) H \Delta u(k) \right) \right), \tag{3}$$

where weight matrices Q_e, H are positive definite with appropriate dimensions, Δ is first-order forward difference operator $(\Delta u(k) = u(k+1) - u(k))$, and decay constant $\beta > 0$ is arbitrarily specified.

Remark 2. The inclusion of a quadratic term $\Delta u(k)$ naturally introduces the integral action to the feedback loop. [2] Meanwhile, the exponential factor $e^{2\beta k}$ makes the closed-loop system have exponential asymptotic stability. For the $e(k)e^{\beta k}$ to approach zero as k approaches infinity, it is clearly sufficient, for $e(k)$ to decay faster than $e^{-\beta k}$. (This is equivalent to requiring the closed-loop system to have a degree of stability of at least β.) [36]