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H_∞ model reference adaptive control for switched systems based on the switched closed-loop reference model

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ABSTRACT

This paper is concerned with the problem of H_∞ state tracking model reference adaptive control for switched systems by the multiple Lyapunov functions method. Neither the measurability of the system state nor the solvability of the H_∞ state tracking model reference adaptive control for each individual subsystem is required. First, to improve the transient performance of switched systems, the closed-loop reference model is introduced to switched systems. Second, the H_∞ state tracking model reference adaptive control problem for switched systems is solved by designing adaptive controllers for subsystems and a switching law. Then, a solvability condition of the H_∞ state tracking model reference adaptive control problem for switched systems is developed.

1. Introduction

A switched system is a dynamical system which comprises a family of subsystems and a logical rule. The subsystems are described by continuous or discrete-time differential equations and the logical rule decides which subsystem is being activated [1]. In the past decades, switched systems have drawn extensive attention mainly because they allow one to describe the behavior of many practical or man-made systems which own inherently some jumping characteristics. In the study of switched systems, stability is a key issue and several approaches have been developed so far, such as the common Lyapunov function method, the single Lyapunov function method, the multiple Lyapunov functions method and so on [2–10]. However, most of the current works are focused on switched systems without uncertainties. Dealing with uncertainties, especially for parametric uncertainties, the adaptive control is an effective method. Meanwhile, the adaptive control for switched systems is a difficult topic. One of the main reasons is that the existence of the parametric uncertainties makes the conventional stability analysis methods mentioned above to be not applicable directly. Therefore, the study of the adaptive control for switched systems is more complicated [11–20]. For pre-given switching signals, by using passivity, in [14,16], the problem of controlling multi-modal piecewise linear affine (PWA) systems was studied by designing an MRAC control law, in which, the switch of the reference model is independent from the plant. The results have been extended to discrete-time PWA plants in [18]. The problem of controlling bimodal piecewise linear affine (PWA) systems was investigated in [17] and the adaptive method presented in [17] was experimentally validated in [19]. Besides, in [20], an output based MRAC approach for piecewise linear systems was proposed.

In recent years, model reference control (MRC) has been widely studied. The objective of MRC is to design a controller such that the state or the output of a plant tracks the state or the output of a given reference model as closely as possible.

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For switched systems, the H_∞ tracking MRC problem has been addressed [21–25]. In particular, when the state is fully measurable, [21] investigated the problem of exponential H_∞ output tracking control for a class of switched neutral systems based on the average dwell time approach. When the state is not available for measurement, observer-based tracking control was proposed for switched linear systems in [24]. However, it is worth noting that in [21–24], the reference input is seen as a part of external disturbances, which is not always reasonable. Therefore, it is necessary to search a more effective method to solve this problem, which partly makes motivation for this study.

Although the H_∞ tracking MRC problem has been extensively studied, only a few results focus on the H_∞ tracking MRC problem for switched systems with parametric uncertainties. [26] considered the H_∞ state tracking model reference adaptive control (MRAC) for switched linear systems under the average dwell time method. However, in [26], the system state is assumed to be fully measurable and the H_∞ tracking MRAC problem for each individual subsystem is required to be solvable. Obviously, it put forward high demand for each individual subsystem and is usually hard to be satisfied in practice. Thus, a natural question arises: can we still solve the H_∞ tracking MRAC problem for the switched systems by designing adaptive controllers and a switching law, when the system state is not fully measurable and the problem for each individual subsystem is not solvable? Obviously, this is a challenge problem which has never been solved in the MRAC. This makes another motivation for this study.

On the other hand, it is well known that the restriction of the adaptive control is slow adaptation and poor transient response, especially when there exist large initial estimation errors. For this reason, many researchers have devoted their efforts to improve the transient performance of the adaptive control systems [27–29]. Recently, a class of closed-loop reference model have been proposed to guarantee transient performance, where an observer-like feedback term containing the state error between the reference model and the controlled system is added into the reference model [30–34]. In fact, the transient performance is improved by the introduction of the feedback gain which is designed to shift the eigenvalue of the closed-loop matrix to shape the convergence speed. Therefore, the feedback gain provides one more degree-of-freedom to the adaptive control system and thus has been received growing attention [30–34]. With the closed-loop reference model, [30] and [31] studied the state tracking of MRAC under state measurable and state unmeasurable, respectively. Then, the stability, robustness, transient, as well as oscillations and peaking were analyzed in [32–34]. However, the transient performance of switched adaptive control systems has been rarely addressed, although this is also an important problem. Allowing for this point, in this paper, we construct a switched closed-loop reference model to improve the transient performance of switched systems.

In this paper, H_∞ tracking MRAC problem for switched systems is investigated. We construct a switched closed-loop reference model and the transient performance can be improved by designing the feedback gain for each individual subsystem. The contributions of this note are as follows: first, for switched systems, the closed-loop reference model is introduced to improve the transient performance. Second, the state is not required to be fully measurable. We only use the output and the state of the closed-loop reference model in the design of controllers and adaptive laws. Finally, we do not assume the problem of H_∞ tracking MRAC of any subsystem is to be solvable. We construct a new state by which the switching law is designed and the H_∞ tracking MRAC problem for switched systems is still solved, at the same time, the reference input is not required to be regarded as external disturbance.

Notation: the notation used in this paper is standard. We use $P > 0$ $(P < 0)$ to denote a positive-definite (negative definite) matrix P. A^{-1} represents the inverse of matrix A and A^T represents the transpose of matrix A. I and 0 represent identity matrix and zero matrix in a block matrix, respectively. In a matrix, the symmetric terms are denoted by $*$. $\mathbb{R}^n$ stands for the n-dimensional Euclidean space and $\mathbb{R}^{n\times m}$ is the set of all $n \times m$ real matrices. $L_n^2[0, +)$ is the space of n-dimensional square integrable function vector over $[0, +\infty]$. $\lambda_{\max}(B)$ $(\lambda_{\min}(B))$ is the maximum (minimum) eigenvalue of matrix B. *diag* $\{A, B\}$ represents the block diagonal matrix of A and B. $\|x\| = \sqrt{\sum_{i=1}^{n}|x_i|^2}$: the norm of a vector $x = (x_1, x_2, \ldots, x_n)^T$. $\|A\| = \sqrt{\lambda_{\max}(AA^T)}$: the norm of matrix A.

2. Problem formulation and preliminaries

Consider the switched system

$$\begin{aligned} \dot{x}(t) &= A_\sigma x(t) + B_\sigma \Lambda_\sigma u_\sigma(t) + E_\sigma \omega(t), \\ y(t) &= C_\sigma^T x(t), \end{aligned} \tag{1}$$

where the plant state $x(t) \in \mathbb{R}^n$, the control input $u(t) \in \mathbb{R}^m$, an arbitrary external disturbance $w(t) \in L_n^2[0, \infty)$ and the measurement output $y \in \mathbb{R}^p$. $\sigma(t) : [0, +\infty) \to I = \{1, 2, \ldots, M\}$ is a switching signal which is a piecewise continuous function depending on time or on state or both, and M is the number of subsystems. The matrices A_i, Λ_i are unknown constant matrices, while B_i, C_i are known constant matrices, and only y is assumed to be available for measurement. The switching signal $\sigma(t)$ can be characterized by the switching sequence

$$\sum = \{x_0; (i_0, t_0), (i_1, t_1), \ldots, (i_n, t_n), \ldots | i_n \in I, n \in N\},$$

in which t_0 is the initial time, x_0 is the initial state, and N is the set of nonnegative integers. When $t \in [t_k, t_{k+1})$, $\sigma(t) = i_k$, that is the i_kth subsystem is active. Thus, when $t \in [t_k, t_{k+1})$, the trajectory $x(t)$ of the system (1) is defined as the trajectory $x_{i_k}(t)$ of the i_kth subsystem. It is assumed that only limited number of switches happen in any finite time interval which has been widely used in the study of switched systems [2,3].