



# Sliding mode synchronization of multiple chaotic systems with uncertainties and disturbances



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## ABSTRACT

This paper investigates two classes of synchronization problems of multiple chaotic systems with unknown uncertainties and disturbances by employing sliding mode control. Modified projective synchronization and transmission synchronization are discussed here. For the modified projective synchronization problem, sliding mode controllers are designed to ensure that multiple response systems synchronize with one drive system under the effects of external disturbances. For the transmission synchronization problem, based on adaptive sliding mode control, an integral sliding surface is selected and the adaptive laws are derived to tackle unknown uncertainties and disturbances for such systems. A class of nonlinear adaptive sliding mode controllers is developed to guarantee asymptotical stability of the error systems so that all chaotic systems can synchronize with each other. Simulation results are given to illustrate the effectiveness of the proposed schemes by comparing with the existing methods.

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## 1. Introduction

Synchronization [1] of multiple chaotic systems has become a hot topic in recent years. It has a bright future for multilateral communications and many other engineering fields in both theory and practice [2–5]. Various kinds of synchronization among multiple chaotic systems have been discussed, such as complete synchronization [6–8], anti-synchronization [9], projective synchronization, hybrid synchronization [10], combination synchronization [11,12]. Two kinds of synchronization modes have been introduced to connect multiple chaotic systems. One is multiple response systems synchronize with one drive system, and the other is the ring transmission synchronization mode among multiple systems with a ring connection [8,13–15]. These modes have been successfully applied in complex networks and information engineering. Many synchronization control schemes have been developed, such as linear and nonlinear feedback control [6,7], the direct design method [8–10], impulsive control [16], sample-data control [17], hybrid control [18]. However, most of the studies aforementioned

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are only concerned with the synchronization of multiple deterministic systems and do not consider the influences of some uncertainties for such systems.

For chaos synchronization, unknown model uncertainties have a bad affect on chaotic systems' dynamics and synchronization behavior, and degrade the performance of real systems. Therefore, researchers have devoted their efforts to investigate the synchronization of chaotic systems with different kinds of uncertainties by adopting adaptive control approaches. For example, synchronization of chaotic systems with unknown parameters has been investigated in various studies [19,20]. Zhang et al. addressed the exponential synchronization control problem for a class of Genesio–Tesi chaotic systems by considering partially known uncertainties [21]. Synchronization of chaotic systems with disturbances or non-identical perturbations has been proposed [22,23]. Leung et al. gave a simple adaptive-feedback scheme to synchronize chaotic systems with uncertain parameters [24]. Chen et al. discussed adaptive control of multiple chaotic systems with unknown parameters [25]. Unfortunately, almost all of these works only deal with the synchronization problems between two uncertain chaotic systems. Up to now, a few of related results have been established for the synchronization of multiple uncertain chaotic systems, which is the main motivation of this work.

On another research frontier, sliding mode control method [26] is an effective way to deal with uncertainties due to its advantages of fast dynamic response and low sensitivity to external disturbances and model uncertainties, and many important results have been presented in some literatures. For example, Zheng et al. studied quantization feedback control of uncertain systems based on sliding mode control technique [27,28]. Li et al. successfully applied adaptive sliding mode control method to uncertain fuzzy systems [29]. Zhang et al. discussed chaos control for a class of uncertain chaotic system using an adaptive chatter free sliding mode control method [30]. Cao et al. used sliding mode control to deal with synchronization of master-slave markovian switching complex dynamical networks [31].

In the past few years, increasing numbers of issues in sliding mode synchronization of chaotic systems with uncertainties have been discussed by lots of scholars. Cai et al. designed a sliding mode controller for modified projective synchronization of chaotic systems with disturbances [32]. Aghababa and Heydari investigated the synchronization problem for two different uncertain chaotic systems with input nonlinearities, model uncertainties, external disturbances and unknown parameters [33]. Robust adaptive sliding mode control was used to achieve the synchronization of two uncertain hyperchaotic systems [34]. Sun et al. studied the finite-time synchronization of two complex-variable chaotic systems using nonsingular sliding mode control [35]. Adaptive sliding mode controllers with input nonlinearity were proposed for two uncertain chaotic systems [36–38]. For the reduction of chattering, adaptive sliding mode controllers were presented to synchronize uncertain chaotic systems [39,40]. From the above mentioned results, studies using sliding mode control methods for the synchronization of uncertain chaotic systems have been limited to two chaotic systems with unknown parameters, uncertainties and external disturbances. Hence, another motivation of this paper is to synchronize multiple uncertain chaotic systems using adaptive sliding model control.

In response to the above discussions, in this paper, a modified projective synchronization control problem of multiple chaotic systems with disturbances is firstly investigated to ensure that multiple response systems synchronize with one drive system. Furthermore, the adaptive laws and sliding mode controllers including nonlinearities are proposed to realize transmission synchronization among multiple chaotic systems with uncertainties and external disturbances. Finally, two simulation examples are given to demonstrate the effectiveness of the proposed synchronization schemes by comparing with some closely relating works. The main contributions of this paper lie in: 1) Synchronization among multiple uncertain chaotic systems is first discussed using sliding mode control. 2) Two kinds of important network synchronization modes are investigated to synchronize multiple chaotic systems. 3) We deal with unknown uncertainties and disturbances among multiple uncertain chaotic systems by designing a class of adaptive sliding mode controllers, which have a better control performance than some existing results.

## 2. Modified projective synchronization of multiple chaotic systems with disturbances

This section discusses the modified projective synchronization problem of multiple chaotic systems, which has one drive system that synchronizes with multiple response systems. The controller design problem is taken into account based on sliding mode control. An example is given, and simulation results are analyzed to show the effectiveness of the control method.

Consider the following  $N$  chaotic systems with disturbances, the first system is described by:

$$\begin{cases} \dot{x}_{11}(t) = A_{11}x_1 + f_{11}(x_1(t)) + d_{11}(t), \\ \dot{x}_{12}(t) = A_{12}x_1 + f_{12}(x_1(t)) + d_{12}(t), \\ \vdots \\ \dot{x}_{1n}(t) = A_{1n}x_1 + f_{1n}(x_1(t)) + d_{1n}(t), \end{cases} \quad (2.1)$$

where  $x_1(t) = [x_{11}, x_{12}, \dots, x_{1n}]^T$  is the state of the system (2.1),  $f_{11}(x_1), f_{12}(x_1), \dots, f_{1n}(x_1)$  are continuous functions,  $f_1(x_1(t)) = [f_{11}, f_{12}, \dots, f_{1n}]^T$ ;  $A_1 = [A_{11}, A_{12}, \dots, A_{1n}]^T$  is a coefficient matrix, and the disturbances of the system (2.1) are

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