Neurocomputing 171 (2016) 1131–1138

Contents lists available at ScienceDirect

Neurocomputing

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

Robust adaptive finite-time synchronization of nonlinear resource management system ☆

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ARTICLE INFO

Article history:
Received 1 March 2015
Received in revised form
3 May 2015
Accepted 19 July 2015
Communicated by H. Jiang
Available online 6 August 2015

Keywords:
Nonlinear resource management system
Robust finite-time synchronization
Terminal attractors
Adaptive control

ABSTRACT

In this paper, the robust adaptive finite-time synchronization problem for nonlinear resource management system with uncertain parameters is discussed. By incorporating the finite-time stability theory and adaptive control approach, a novel and more general adaptive finite-time synchronization control scheme is proposed. The developed result depends on the terminal attractors, which can not only guarantee the robust synchronization of nonlinear resource management system with uncertain parameters in finite-time, but also can guarantee the uncertain parameters to be identified effectively simultaneously. Furthermore, due to the tuning parameters of the terminal attractors, a faster synchronization speed can be obtained by adjusting the parameters in the designed controllers. Finally, an illustrative example with simulation results is provided to illustrate and verify the effectiveness of the proposed control scheme.

1. Introduction

In the past few decades, with the continuous development of economy, the issue of energy resources supply and demand has attracted more and more attention from local governments and enterprises. One of the most important problems in the field of energy-resource management is how to keep the energy resources in one region to be stable and balanced, in other words, the related strategies should meet the requirement of energy resources shortage as fast as possible.

Considering the variations of energy resources in time scale, the dynamical system seems to be an appropriate approach to investigate this complex system. A three-dimensional resource demand–supply system was proposed by Sun et al. [1], which displays a complex 2-scroll attractor without consideration of the renewable energy resources. Based on this model, the authors in [2] studied chaos synchronization by using linear control method. In [3], by using feedback control and adaptive control methods, the chaotic resource management system was controlled to the equilibrium points. By introducing a new variable denoting the renewable energy resource, a four-dimensional resource management system was proposed in [4]. It was shown that this four-dimensional nonlinear system can exhibit some interesting dynamic characteristics. In [5], the authors investigated synchronization of this nonlinear system based on feedback control approach. In [6], the authors studied the robust chaos synchronization problem for the four-dimensional resource management system by using adaptive control approach. In [7], by taking into account stochastic noises, the authors considered stochastic synchronization of resource management system. Since the pioneer work in [8], chaos control and synchronization of chaotic systems have been intensively studied, and lots of results and synchronization methods have been developed in the past decades, such as synchronization of neural networks [9–14], and synchronization of complex networks [15–18], and for the other relevant results, please refer to [19,20], and the references therein. However, due to the nonlinear coupling and complex nonlinear properties, control and synchronization of nonlinear resource management system is still worth considering.

On the other hand, in many practical engineering processes, it is more valuable to synchronize in *a finite time* rather than merely asymptotically, such as digital communication [21]. To achieve this faster or finite-time purpose in control systems, an effective method is the finite-time control method [22–26]. In [27], the authors considered the finite-time synchronization of unified chaotic system with uncertain parameters, where the continuous controller designing approach was presented, however, there were no tuning parameters in the designed controller, which would make it not to be applicable and affect the synchronization speed. In [28], the authors discussed the finite-time synchronization of complex networks with stochastic

☆This work was supported in part by the Soft Science Research Plan of Science and Technology Department of Jiangsu Province under Grant BR2014005, and in part by the Philosophy and Social Science Foundation of Higher Education in Jiangsu Province under Grant 2010SJD630064.

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http://dx.doi.org/10.1016/j.neucom.2015.07.074
0925-2312/

noises. Subsequently, some adaptive approaches have been proposed, in [29], the authors considered the finite-time stabilization via adaptive terminal sliding mode control method. In [30], the authors studied the finite-time stabilization of chaotic systems, where the proposed adaptive control law needed one of the state variables not to be zero. However, to the best of the authors' knowledge, there are few results considering finite-time synchronization and parameter identification of nonlinear resource management system with uncertain parameters, not to mention the adaptive finite-time synchronization of this nonlinear system, so this problem still remains open and challenging. Therefore, in this paper, based on the above discussions, the robust finite-time synchronization of nonlinear resource management system with uncertain parameters is discussed in detail based on the finite-time stability theory. By adjusting the parameters of the terminal attractors, finite-time synchronization of nonlinear resource management system can be realized, and a faster synchronization speed could also be obtained.

The remaining of the paper is organized as follows. In Section 2, the nonlinear resource management system is presented and the robust finite-time synchronization issue is formulated. In Section 3, a novel robust adaptive finite-time synchronization controller designing approach based on the terminal attractors is proposed, sufficient conditions are developed to realize the robustly adaptive synchronization in finite time, and the uncertain parameters could also be identified effectively at the same time. In Section 4, an illustrative example is given to demonstrate the effectiveness and usefulness of the obtained results. At last, this paper completes with a conclusion.

2. Notations and preliminaries

In this paper, the four-dimensional nonlinear resource system proposed by Sun et al. [4] is considered, which seems to be a suitable way of describing the actual energy demand–supply and instructive for the resource demand–supply in some regions of China. The nonlinear dynamic model is formulated as

$$\begin{cases} \dot{x} = a_1 x(1 - x/M) - a_2(y+z) - d_3 w, \\ \dot{y} = -b_1 y - b_2 z + b_3 x[N - (x - z)], \\ \dot{z} = c_1 z(c_2 x - c_3), \\ \dot{w} = d_1 x - d_2 w, \end{cases} \tag{1}$$

where $x(t)$ is the resources shortage in region A, $y(t)$ is the resources supply increment in region B, $z(t)$ is the resources import in region A, $w(t)$ is the renewable resources in region A, such as wind power and wave power. The system parameters M, N, a_i, b_j, c_j, d_j $(i = 1, 2; j = 1, 2, 3)$ are all set as the positive real parameters, and it is found that if the parameters are chosen as $a_1 = 0.09, a_2 = 0.15, b_1 = 0.06, b_2 = 0.083, b_3 = 0.07, c_1 = 0.2, c_2 = 0.5, c_3 = 0.4, d_1 = 0.1, d_2 = 0.06, d_3 = 0.08, M = 1.8, N = 1.0$, this nonlinear system can exhibit chaotic behavior [4].

The main purpose of the paper is to study the robust finite-time synchronization of nonlinear resource management system by using adaptive control approach. Based on the master–slave synchronization scheme, the master system is given by

$$\begin{cases} \dot{x}_m = a_1 x_m - a_2(y_m + z_m) - a_3 x_m^2 - d_3 w_m, \\ \dot{y}_m = -b_1 y_m - b_2 z_m - b_3 x_m(x_m - z_m) + b_4 x_m, \\ \dot{z}_m = r_1 x_m z_m - r_2 z_m, \\ \dot{w}_m = d_1 x_m - d_2 w_m, \end{cases} \tag{2}$$

where $a_3 = a_1/M, b_4 = b_3 N, r_1 = c_1 c_2, r_2 = c_1 c_3$.

Without loss of generality, assume all the parameters to be unknown, then the corresponding slave system with uncertain parameters can be formulated by

$$\begin{cases} \dot{x}_s = \hat{a}_1 x_s - \hat{a}_2(y_s + z_s) - \hat{a}_3 x_s^2 - \hat{d}_3 w_s + u_1, \\ \dot{y}_s = -\hat{b}_1 y_s - \hat{b}_2 z_s - \hat{b}_3 x_s(x_s - z_s) + \hat{b}_4 x_s + u_2, \\ \dot{z}_s = \hat{r}_1 x_s z_s - \hat{r}_2 z_s + u_3, \\ \dot{w}_s = \hat{d}_1 x_s - \hat{d}_2 w_s + u_4, \end{cases} \tag{3}$$

where $\hat{a}_1, \hat{a}_2, \hat{a}_3, \hat{b}_1, \hat{b}_2, \hat{b}_3, \hat{b}_4, \hat{r}_1, \hat{r}_2, \hat{d}_1, \hat{d}_2, \hat{d}_3$ are the uncertain parameters to be estimated, and u_1, u_2, u_3, u_4 are the controllers to be designed appropriately.

Define the error variables as $e_1 = x_s - x_m, e_2 = y_s - y_m, e_3 = z_s - z_m, e_4 = w_s - w_m$, then the error system between systems (2) and (3) can be derived by

$$\begin{cases} \dot{e}_1 = e_{a_1} x_s + a_1 e_1 - e_{a_2}(y_s + z_s) - a_2(e_2 + e_3) - e_{a_3} x_s^2 - a_3 e_1(x_s + x_m) - e_{d_3} w_s - d_3 e_4 + u_1, \\ \dot{e}_2 = -e_{b_1} y_s - b_1 e_2 - e_{b_2} z_s - b_2 e_3 \\ \quad - e_{b_3} x_s(x_s - z_s) - b_3 x_s(x_s - z_s) + b_3 x_m(x_m - z_m) + e_{b_4} x_s + b_4 e_1 + u_2, \\ \dot{e}_3 = e_{r_1} x_s z_s + r_1(e_1 z_s + e_3 x_m) - e_{r_2} z_s - r_2 e_3 + u_3, \\ \dot{e}_4 = e_{d_1} x_s + d_1 e_1 - e_{d_2} w_s - d_2 e_4 + u_4, \end{cases} \tag{4}$$

where $e_{a_i} = \hat{a}_i - a_i (i = 1, 2, 3), e_{b_i} = \hat{b}_i - b_i (i = 1, 2, 3, 4), e_{d_i} = \hat{d}_i - d_i (i = 1, 2, 3)$ and $e_{r_i} = \hat{r}_i - r_i (i = 1, 2)$ are the estimation errors of the uncertain parameters, respectively.

For convenience, one can further deduce

$$\begin{cases} \dot{e}_1 = e_{a_1} x_s + a_1 e_1 - e_{a_2}(y_s + z_s) - a_2(e_2 + e_3) - e_{a_3} x_s^2 - a_3 e_1(x_s + x_m) - e_{d_3} w_s - d_3 e_4 + u_1, \\ \dot{e}_2 = -e_{b_1} y_s - b_1 e_2 - e_{b_2} z_s - b_2 e_3 \\ \quad - e_{b_3} x_s(x_s - z_s) - b_3 e_1(x_s + x_m) + b_3 e_1 z_s + b_3 e_3 x_m + e_{b_4} x_s + b_4 e_1 + u_2, \\ \dot{e}_3 = e_{r_1} x_s z_s + r_1(e_1 z_s + e_3 x_m) - e_{r_2} z_s - r_2 e_3 + u_3, \\ \dot{e}_4 = e_{d_1} x_s + d_1 e_1 - e_{d_2} w_s - d_2 e_4 + u_4. \end{cases} \tag{5}$$

Therefore, the next step of the paper is to design some suitable controllers to guarantee the error system (5) to be robustly asymptotically stable in finite time, that is, the slave system (3) can robustly synchronize the master system (2) with uncertain parameters by using the designed controllers in finite time.

Now, it is ready to introduce the following definition and lemma in advance, which will be used in the proof of the main results.

Definition 1 (*Haimo [22]*). Consider the following nonlinear dynamic system

$$\dot{x} = f(x), \tag{6}$$

where $x \in R^n$ is the system state, and f is a smooth nonlinear function. If there exists a constant $t^* > 0$ (t^* may depend on the initial condition $x(0)$), such that

$$\lim_{t \to t^*} \| x(t) \| = 0, \tag{7}$$

and $\| x(t) \| \equiv 0$, if $t \geq t^*$, then system (6) is called the finite-time stable.

Lemma 1 (*Wang et al. [25]*). *If there exists a positive-definite function $V(t)$ satisfies*

$$\dot{V}(t) \leq -c V^{\beta}(t), \quad \forall t \geq t_0, \ V(t_0) \leq 0, \tag{8}$$

where $c > 0$ and $0 < \beta < 1$ are two constants. Then for any initial time t_0, $V(t)$ satisfies

$$V^{1-\beta}(t) \leq V^{1-\beta}(t_0) - c(1-\beta)(t - t_0), \quad t_0 \leq t \leq t_1, \tag{9}$$

and

$$V(t) \equiv 0, \quad \forall t \geq t_1,$$