2013년 8월 전자공학회 논문지 제 50 권 제 8 호
Journal of The Institute of Electronics Engineers of Korea Vol. 50, NO. 8, August 2013 http://dx.doi.org/10.5573/ieek.2013.50. 8.292

논문 2013-50-8-35

비동일 노드들과 연결정보 제약이 없는 복잡동적 네트워크의 동기화

(Synchronization of a Complex Dynamical Network with nonidentical Node and Free Coupling Strength)

윤 한 오*

(Han-O YUN©)

요 약

본 논문은 동일하지 않는 노드들을 갖는 복잡동적 네트워크의 동기화문제를 고려한다. 이 문제에서 타켓 노드는 별도의 독립노드 대신에 네트워크내의 한 노드를 택하였다. 더욱이 본 논문의 동기화기법에서는 기존에 존재하는 연결행렬의 정보나 부가적인 조건을 필요하지 않는 장점이 있다. 리아프노프 안정성기법에 의거하여 타켓 노드와 다른 노드들 사이의 동기화를 위한 새로운 적응제어기를 위한 조건을 유도한다. 마지막으로 제안된 기법의 효율성을 보이기 위하여 수치적인 예제를 제시한다.

Abstract

This paper considers synchronization problem of a complex dynamical network with nonidentical nodes. For the problem, the target node is chosen as one of nodes in the complex network instead of an isolate node. Moreover, our synchronization scheme does not need additional conditions and information of coupling matrix comparing with existing works. Based on Lyapunov stability theory, a design criterion for a novel adaptive feedback controller for the synchronization between the target node and another nodes of the complex network is proposed. Finally, the proposed method is applied to a numerical example in orther to show the effectiveness of our results.

Keywords : complex dynamical network, synchronization, free coupling matrix, nonidentical node, Lyapunov method.

Ⅰ. Introduction

During the last decade, complex dynamical networks, which are a set of interconnected nodes with specific dynamics, have been attracted increasing attention in various fields such as physics, biology, chemistry and computer science[1~5]. As science and society develop, our everyday lives have been closed to complex networks, for instance, transportation networks, World Wide Web, coupled biological and chemical engineering systems, neural networks, social networks, electrical power grids, global economic markets and so on.

Among various research topics about complex dynamical networks, synchronization is one of the most significant and interesting phenomena([6~12, 14~16]). Synchronization of a complex dynamical networks can be divided into two point of view. One is the synchronization of a complex dynamical network that

* 정회원, 구미대학교 컴퓨터정보전자과
(Dept. of Computer Information & Electronics, Gumi University)
© Corresponding Author(E-mail: yho@gumi.ac.kr)
접수일자: 2013년5월3일, 수정완료일: 2013년7월22일

is called "inner synchronization"[7~12]. It means that all the nodes in a complex network eventually approach to trajectory of a target node. Another is called "outer synchronization"[14~16] which considers the synchronization between two or more complex networks regardless of synchronization of inner network. In this paper, a new control problem for inner synchronization will be investigated.

Until now, most of researchers on inner synchronization of a complex network used an isolated node[7~11] as a target system. This scheme has connection between an isolate node and all the nodes of a complex network as one to one correspondence. This is, a complex network with N nodes has additional N connections with the isolated node except of inner connection in the network. Note that this is a strong assumption, since the behavior of the network depends on the collective dynamics and not to an isolated node[12].

On the contrary, if we select a target node to one of nodes in a complex network, then we do not set up an isolate node and can achieve synchronization by using original connection of a complex network without any more connections.

Synchonization of a complex dynamical network have been well noticed that many researchers adopt the assumption that the dynamics of all nodes are identical. However, this assumption is unlikely environment in most of complex dynamical networks. For example, in a swarm robot system, every individual robots have different dynamics among them. Even if the swarm robot system is consisted of same robots, it has possibility to be a nonidentical network system due to uncertainties, parameter aging, saturation, and so on. The synchronization schemes for complex networks with identical nodes developed in the literature can not be directly applied to the networks with nonidentical nodes due to different dynamics in each nodes. Therefore, the necessity of further investigation of new synchonization schemes for a complex dynamical network with nonidentical nodes is strongly raised. In addition, only a few papers have been studied the synchronization problem with nonidentical nodes until now.

As is well known, there are some basic assumptions in previous works to handle with complex networks. Examples are that coupling matrix is symmetric, zero sum of row and diagonalizable[13]. These assumption make easy to control and analytic the complex dynamical networks, but it is not realistic assumptions because many real network systems such as WWW or genetic network do not satisfy the assumptions. On the other hand, there are such works that do not need any conditions of coupling matrix. This coupling matrix is called free coupling matrix. Moreover, the coupling matrix is generally unknown or uncertain in actual real systems. In that case, adaptive control schemes in order to deal with unknown coupling matrix are utilized in the literature[14~15]. However, these studies accomplish synchronization by estimating all entries of coupling matrix. In other words, if the number of nodes is N, then the number of parameters which should be estimated should be N^2. This procedure is not valuable and effective in real systems because the number of nodes is usually so big in practical complex networks. Therefore, the development of new approaches which reduce parameters that will be estimated should be necessary.

Motivated by the above discussion, we will further investigate a complex network with nonidentical node unlike previous works which usually treated a complex network with identical nodes. Furthermore, any assumptions about coupling matrix are not given in our proposed approach. Also, unknown free coupling strength is considered. In order to handle unknown free coupling matrix, we estimate some parameters of entries of coupling matrix by appling an adaptive control scheme. It should be noted that our control scheme does not need to estimate all entries of the unknown coupling matrix. For development of a new synchronization scheme, we do not use an isolate node as a target node because of its unreality. Instead of it, we select one of nodes consisting of a complex network as a target node. It means that our synchronization scheme is a method to use original connections of a complex network without imposing additional connections. Finally, the dynamic model such as small-world network with free weight are considered in order to show asymptotic synchronization between the target node and another nodes.

This paper is organized as follows, In Section Ⅱ, some preliminary results are a general dynamical complex network. A numerical example is given in Section Ⅳ to show the effectiveness of the derived results. Conclusions are drawn in Section Ⅴ.

Ⅱ. Preliminaries

Consider a complex dynamical network consisting of N linearly coupled nodes described by

$$\dot{x}_i(t) = f_i(x_i(t)) + \sum_{j=1}^{N} c_{ij} x_j(t) + u_i(t),\ i = 1,2...,N \tag{1}$$

where $x_i = (x_{i1}, x_{i2}, ..., x_{\in})^T \in \mathrm{R}^n$ is the state vector of the ith node, f_i : $\mathrm{R}^n \to \mathrm{R}^n$ are a smooth nonlinear field, $u_i(t)$ are control input of node ith node, and C = $(C_{ij})_{N\times N}$ is the coupling configuration matrix representing the coupling strength and the topological structure of the network, in which c_{ij} is nonzero if there is a connection from node i to node $j(i \neq j)$, and is zero otherwise. For our synchronizati on scheme, let us define error vectors as follows

$$e_i(t) = x_l(t) - x_i(t),\ \ i = 1,2,...,N \tag{2}$$

where l is the target node number in the complex dynamical network system (1). It should be noted that the control input of the target node is not required, $i.e., u_l(t) = 0$.

Definition 1. A complex network is said to achieve asymptotically inner synchronization, if $\lim_{t\to\infty} \| x_l - x_i \| \to 0$ for all $0 < i < N$, where a constant $l, 0 < l < N$, is a target node number.

Remark 1. Most of the study about synchronization in a complex network are used an isolated node denoted by $s(t)$ as a target[7~11]. In order words, their goal is to make each node to the isolate node, $x_1(t) = x_2(t) = ...x_N(t) = s(t)$. However, from a practical point of view, the hypothesis of setting an isolate node is effective under very limited environment. So it is very worth to deal with the synchronization between a target node and another nodes in the complex network.

For convenience shake, we choose first ode as a trget node. So Eq.(2) can be rewritten

$$e_i(t) = x_1(t) - x_i(t),\quad i = 2,...,N \tag{3}$$

where $e_1(t) = x_1(t) - x_1(t)$ is zero. Therefore, from now, we only need to consider $e_i(t), (i = 2,...,N)$.

Remark 2. It should be noted that there are no any constraint of coupling matrix C such as symmetric or $c_{ii} = -\sum_{j=1, j\neq i}^{N} c_{ij}\ (i = 1,2,...,N)$ in this paper, so any coupling matrix can be used. However, most of researchers set constraint on coupling strength, c_{ij}, in order to easily develop synchronization schemes[6~12], but there is a slight chance that the complex networks in real world have this kind of structures. Thus, our problem handling with free coupling matrix is more difficult and practical jobs.

III. Main results

In this section, we will investigate the synchronization between a target node and another nodes ina complex network(1), and present adaptive control method with update laws by using Lyapunov stability analysis.

Theorem 1. Let the adaptive control be

$$u_i(t) = \overrightarrow{f_i}(t) + d_i(t) e_i(t) + a_i(t) x_i(t) \tag{4}$$

with $\overrightarrow{f_i}(t)=f_1(t)-f_i(t)$ and the following updating laws

$$\dot{d}_i(t)=\|e_i(t)\|^2,\ \dot{a}_i(t)=e_i^T(t)x_i(t) \tag{5}$$

Then, all nodes in the complex network system(1) is synchronized with the target node in the network.

Remark 3. in theorem 1, the control input does not use any information on coupling strength so that our synchronization scheme can be applied to a complex network with unknown coupling matrix. It is the very useful approach on control point of view.

Proof. The error system can be described by :

$$\begin{aligned}\dot{e}_i(t)&=f_1(x_1(t)-f_i(x_i(t))\\&\quad+\sum_{j=1}^{N}(c_{ij}-c_{ij})x_j(t)-u_i(t).\ i=2,...,N.\end{aligned} \tag{6}$$

The error dynamics (6) can be rewritten by

$$\dot{e}(t)=$$
$$\begin{bmatrix}\overline{f_2}(t)\\ \overline{f_3}(t)\\ \vdots\\ \overline{f_N}(t)\end{bmatrix}+\begin{bmatrix}c_{11}-c_{21} & c_{12}-c_{22} & \cdots & c_{1N}-c_{2N}\\ c_{11}-c_{31} & c_{12}-c_{32} & \cdots & c_{1N}-c_{3N}\\ \vdots & \vdots & & \vdots\\ c_{11}-c_{N1} & c_{12}-c_{N2} & \cdots & c_{1N}-c_{NN}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\\ \vdots\\ x_N(t)\end{bmatrix}-\begin{bmatrix}u_1(t)\\ u_2(t)\\ \vdots\\ u_N(t)\end{bmatrix} \tag{7}$$

where $e(t)=[e_2^T(t),e_2^T(t),\ldots,e_N^T(t)]^T\in R^{(n\times(N-1))}$.

By Eq.(3), Eq.(7) can be modified to

$$\dot{e}(t)=\begin{bmatrix}\overline{f_2}(t)\\ \overline{f_3}(t)\\ \vdots\\ \overline{f_N}(t)\end{bmatrix}+\begin{bmatrix}c_{11}-c_{21} & 0 & \cdots & 0\\ 0 & c_{11}-c_{31} & \cdots & 0\\ \vdots & \vdots & & \vdots\\ 0 & 0 & \cdots & c_{11}-c_{N1}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\\ \vdots\\ x_N(t)\end{bmatrix}+$$

$$\begin{bmatrix}c_{12}-c_{22} & c_{13}-c_{23} & \cdots & c_{1N}-c_{2N}\\ c_{12}-c_{32} & c_{13}-c_{33} & \cdots & c_{1N}-c_{3N}\\ \vdots & \vdots & & \vdots\\ c_{12}-c_{N2} & c_{13}-c_{N3} & \cdots & c_{1N}-c_{NN}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\\ \vdots\\ x_N(t)\end{bmatrix}-\begin{bmatrix}u_1(t)\\ u_2(t)\\ \vdots\\ u_N(t)\end{bmatrix}=\begin{bmatrix}\overline{f_2}(t)\\ \overline{f_3}(t)\\ \vdots\\ \overline{f_N}(t)\end{bmatrix}+$$

$$\begin{bmatrix}c_{11}-c_{21}+c_{12}-c_{22} & c_{13}-c_{23}\cdots & c_{1N}-c_{2N}\\ c_{12}-c_{32} & c_{11}-c_{31}+c_{13}-c_{23}\cdots & c_{1N}-c_{3N}\\ \vdots & \vdots & \vdots\\ c_{12}-c_{N2} & c_{13}-c_{N3}\cdots & c_{11}-c_{N1}+c_{1N}-c_{NN}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\\ \vdots\\ x_N(t)\end{bmatrix}$$

$$-\begin{bmatrix}c_{12}-c_{22} & c_{13}-c_{23} & \cdots & c_{1N}-c_{2N}\\ c_{12}-c_{32} & c_{13}-c_{33} & \cdots & c_{1N}-c_{3N}\\ \vdots & \vdots & & \vdots\\ c_{12}-c_{N2} & c_{13}-c_{N3} & \cdots & c_{1N}-c_{NN}\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_1(t)\\ \vdots\\ x_1(t)\end{bmatrix}+$$

$$\begin{bmatrix}c_{12}-c_{22} & c_{13}-c_{23} & \cdots & c_{1N}-c_{2N}\\ c_{12}-c_{32} & c_{13}-c_{33} & \cdots & c_{1N}-c_{3N}\\ \vdots & \vdots & & \vdots\\ c_{12}-c_{N2} & c_{13}-c_{N3} & \cdots & c_{1N}-c_{NN}\end{bmatrix}\begin{bmatrix}x_2(t)\\ x_3(t)\\ \vdots\\ x_N(t)\end{bmatrix}-\begin{bmatrix}u_2(t)\\ u_3(t)\\ \vdots\\ u_N(t)\end{bmatrix} \tag{8}$$

Eq.(8) is further simplified to

$$\dot{e}(t)=\begin{bmatrix}\overline{f_2}(t)\\ \overline{f_3}(t)\\ \vdots\\ \overline{f_N}(t)\end{bmatrix}+\begin{bmatrix}-(c_{11}-c_{21}) & -(c_{12}-c_{22}) & \ldots & -(c_{1N}-c_{2N})\\ -(c_{11}-c_{31}) & -(c_{12}-c_{32}) & \ldots & -(c_{1N}-c_{3N})\\ \vdots & \vdots & & \vdots\\ -(c_{11}-c_{N1}) & -(c_{12}-c_{N2}) & \ldots & -(c_{1N}-c_{NN})\end{bmatrix}e(t)$$

$$+\begin{bmatrix}\overline{a_2}x_1(t)\\ \overline{a_3}x_1(t)\\ \vdots\\ \overline{a_N}x_1(t)\end{bmatrix}-\begin{bmatrix}u_2(t)\\ u_3(t)\\ \vdots\\ u_N(t)\end{bmatrix} \tag{9}$$

where $\overline{a_i}=\sum_{j=1}^{N}(c_{1j}-c_{ij})$.

substituting the control input (4) into Eq.(9) gives

$$\dot{e}(t)=-\begin{bmatrix}d_2e_2(t)\\ d_3e_3(t)\\ \vdots\\ d_Ne_N(t)\end{bmatrix}+\begin{bmatrix}-(c_{12}-c_{22}) & -(c_{13}-c_{23}) & \ldots & -(c_{1N}-c_{2N})\\ -(c_{12}-c_{32}) & -(c_{13}-c_{33}) & \ldots & -(c_{1N}-c_{3N})\\ \vdots & \vdots & & \vdots\\ -(c_{12}-c_{N2}) & -(c_{13}-c_{N3}) & \ldots & -(c_{1N}-c_{NN})\end{bmatrix}e(t)$$

$$+\begin{bmatrix}(\overline{a_2}-a_2)x_1(t)\\ (\overline{a_3}-a_3)x_1(t)\\ \vdots\\ (\overline{a_N}-a_N)x_1(t)\end{bmatrix} \tag{10}$$

Now, for stability analysis, let us Lyapunov function as follows

$$V=\frac{1}{2}\sum_{i=2}^{N}e_i^Te+\frac{1}{2}\sum_{i=2}^{N}(d_i-\overline{d_i})^2+\frac{1}{2}\sum_{i=2}^{N}(\overline{a_i}-a_i)^2 \tag{11}$$

where $\overline{d_i}$ are positive constraints to determined.

By calculating the derivative of Lyapunov function (11) with adaptive controller (4) and update law (5), we obtain

$$\dot{V}=\sum_{i=2}^{N}e_i^Te+\sum_{i=2}^{N}(d_i-\overline{d_i})\ \dot{d_i}-\sum_{i=2}^{N}(\overline{a_i}-a_i)\dot{a_i}$$

$$=e^T(t)\begin{bmatrix} -\overline{d_2}-(c_{12}-c_{22}) & -(c_{13}-c_{23}) & \cdots & -(c_{1N}-c_{2N}) \\ -(c_{12}-c_{32}) & -\overline{d_3}-(c_{13}-c_{33}) & \cdots & -(c_{1N}-c_{3N}) \\ \vdots & \vdots & & \vdots \\ -(c_{12}-c_{N2}) & -(c_{13}-c_{N3}) & \cdots & -\overline{d_N}-(c_{1N}-c_{NN}) \end{bmatrix}e(t)$$

$$=e^T(t)\begin{bmatrix} -\overline{d_2}-(c_{12}-c_{22}) & -(c_{13}-c_{23}) & \cdots & -(c_{1N}-c_{2N}) \\ -(c_{12}-c_{32}) & -\overline{d_3}-(c_{13}-c_{33}) & \cdots & -(c_{1N}-c_{3N}) \\ \vdots & \vdots & & \vdots \\ -(c_{12}-c_{N2}) & -(c_{13}-c_{N3}) & \cdots & -\overline{d_N}-(c_{1N}-c_{NN}) \end{bmatrix}e(t)$$

$$\equiv -e^T(t)De(t) \tag{12}$$

In order to analyze the stability in theorem 1, the positive constraints $\overline{d_i}$ are utilized in the Lyapunov function (11). However, the information about $\overline{d_i}$ is not needed to construct the control law(4). Therefore if select any constants $\overline{d_i}$, which make matrix D be a positive definite, then the error system (3) is asymtotically stable by Lyapunov stability theory,

$$\dot{V}=-e^T(t)De(t)<0, \tag{13}$$

which completes the proof.

Remark 4. Note that, in Theorem 1, we do not need any information on coupling matrix C. However recent works for synchronization of complex network with unknown coupling matrix should compute all entries or a large number of entries of coupling matrix[14~15]. Their controllers are required N^2integrators to update control inputs in case of N nodes coupled network. But our proposed controller is only utilized N-1 integrators. It can be stated that Theorem 1 is more outstanding and efficient than the methods of existing works.

Ⅳ. Numerical example

In this section, we present one numerical example to show the effectiveness of the proposed method. In this section, we consider small-world network structure with free weight consisting of the nodes. Each nodes are different chaotic systems such as Lorenz[17], Chen[18], L$\ddot{u}$[19], Chen-Lee[20] and genesio-Tesi[21]. They are typical benchmark three dimensinal chaotic systems. Thus, complex network system consisting of five nodes is described by :

$$\dot{x_i}(t)=f_i(x_i(t))+\sum_{j=1}^{N}c_{ij}x_j(t)+u_i(t) \quad i=1,\ldots,5 \tag{14}$$

$f_1(x_1(t))$: Lorenz System
$f_2(x_2(t))$: Chens System
$f_3(x_3(t))$: Lu System
$f_4(x_4(t))$: Chen-Lee System
$f_5(x_5(t))$: Genesio-Tesi System,

where thre dynamic equations of each nodes are given by Table 1.

In this example, we chosen the first node, Lorenz system, as a target node. The constitution of complex dynamical network of this example is illustrated in Fig. 1.

For Theorem 1 and Corollary 1, the free coupling matrix, C, is given by

$$C=0.2\times\begin{bmatrix} -5 & 3 & 1 & -1 & -3 \\ 1 & -3 & 1 & -2 & 3 \\ 1 & -1 & -7 & -1 & -5 \\ -6 & 1 & 5 & -4 & 1 \\ -1 & -4 & 1 & -2 & -6 \end{bmatrix} \tag{15}$$

표 1. 각 노드들의 시스템 식
Table 1. Equations of each nodes.

Lorenz system	Chen system
$\dot{x}_{11}=p_1(x_{12}-x_{11})$ $\dot{x}_{12}=p_3x_{11}-x_{12}-x_{11}x_{13}$ $\dot{x}_{13}=x_{11}x_{12}-p_2x_{12}$ $p_1=10, p_2=8/3, p_3=28$	$\dot{x}_{21}=p_4(x_{22}-x_{21})$ $\dot{x}_{21}=(p_6-p_4)x_{21}+p_6x_{21}-x_{21}x_{23}$ $\dot{x}_{21}=x_{21}x_{21}-p_5x_{23}$ $p_4=35, p_5=3, p_6=28$
L$\ddot{u}$ system	**Chen-Lee system**
$\dot{x}_{31}=p_7(x_{32}-x_{31})$ $\dot{x}_{31}=p_9x_{32}-x_{31}x_{33}$ $\dot{x}_{31}=x_{31}x_{32}-p_8x_{33}$ $p_7=36, p_8=3, p_9=20$	$\dot{x}_{41}=q_1x_{41}-x_{42}x_{43}$ $\dot{x}_{42}=-q_2x_{42}+x_{41}x_{43}$ $\dot{x}_{43}=-q_3x_{43}+(1/3)x_{41}x_{42}$ $q_1=5, q_2=10, q_3=3.8$
Genesio-Tesi system	
$\dot{x}_{51}=x_{52}$ $\dot{x}_{52}=x_{53}$ $\dot{x}_{53}=-q_4x_{51}-q_5x_{52}-q_6x_{53}+x_{51}^2$ $q_4=6,\ q_5=2.92,\ q_6=1.2$	

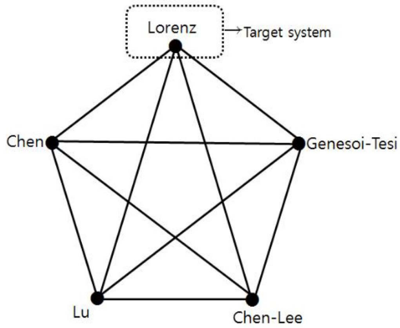

그림 1. 작은 세상 망의 구조
Fig. 1. The structure of small-world network.

In order to show original behavior of the complex network (14) with free coupling (15), the dynamic behaviors of the complex network (14) in absence of controller are depicted in Fig. 2.

As seen in Fig. 2, every nodes of complex network (14) without controller are not synchronized. Our aim is that every nodes of the complex network (14) is synchronized up to target node. For this end, we have applied the controller (4) given in Theorem 1 and then, the results are presented in Fig. 3.

As we can see in Fig. 3, our proposed controller (4) guarantees to achieve asymptotic synchronization. Also, we do not need information of coupling matrix, but our control scheme accomplish our goal by estimating some parameters, $\overline{a_i}$. In order to show

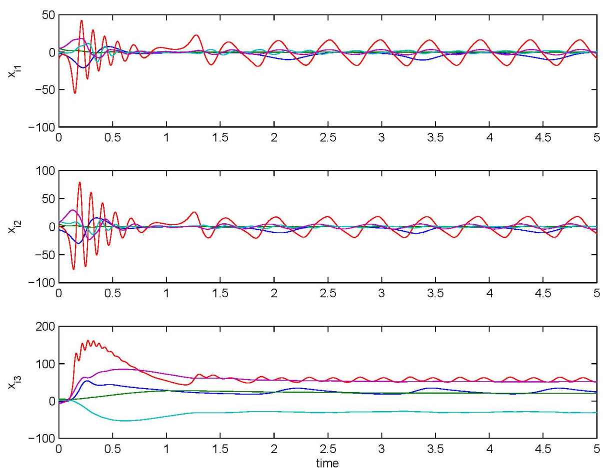

그림 2. 복잡동적망 (14)에서 각 노드들의 상태들
Fig. 2. Evolution of each states in complex network system(14).

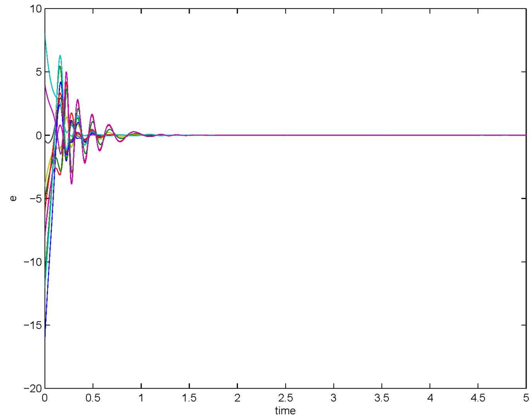

그림 3. 비동일 노드 동적망의 에러 신호들
Fig. 3. Error signals of nonidentical complex network.

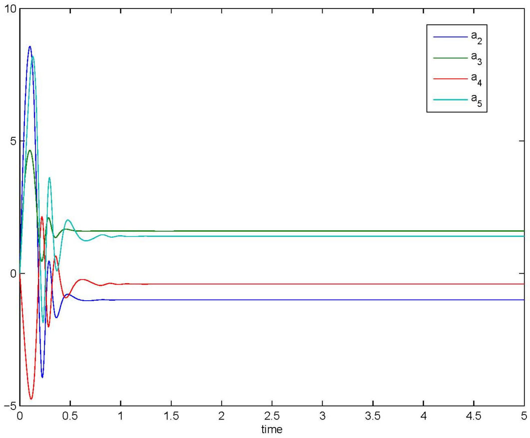

그림 4. 추정된 상태 파라미터들
Fig. 4. Estimated parameters, $a_i = \sum_{j=1}^{N}(c_{1j} - c_{ij}),\ i = 2, \ldots, N.$

estimation results, the initial guess of parameters are chosen as $a_i(0) = 0\ (i = 2, \ldots, N)$.

Fig. 4 displays that estimated parameters approach to true values, $\overline{a_i} = \sum_{j=1}^{N}(a_{1j} - a_{2j})\ i = 2, \ldots, N,$ i.e.,

$$\lim_{t\to\infty} a_2(t) = -1 = \overline{a_2}, \quad \lim_{t\to\infty} a_3(t) = 1.6 = \overline{a_3},$$
$$\lim_{t\to\infty} a_4(t) = -0.4 = \overline{a_4}, \quad \lim_{t\to\infty} a_5(t) = 1.4 = \overline{a_5}.$$

Here, note that only 4 parameters are estimated not all entries of the matrix $C_{5\times5}$ as mentioned in Remark 4.

V. Conclusions

In this paper, the asymptotic synchronization of a complex dynamical network with nonidentical nodes and free coupling matrix is considered. In order to deal with coupling matrix which has no constraint and is unknown, we have developed an adaptive control scheme with less estimating parameters. In addition, we did not take an isolate node for synchronization problem. We just selected a target node in a complex network and used original connection in a complex network in order to achieve our goal. A numerical example has given to show the effectiveness and usefulness of the presented approach.

REFERENCES

[1] S.H. Strogatz, “Exploring complex networks,” Nature 410, pp.268-276, 2001.
[2] A.L. Barabasi, R.Albert, “Emergence of scaling in random networks,” Science 286, pp.509-512, 1999.
[3] S.N. Dorogovtesev, J.F.F. Mendes, “ Evolution of network,” Advances in Physics 51, pp.1079-1187,2002.
[4] M.E.J.Newman, “The structure and function of complex networks,” SIAM Review 45 pp.167-256, 2003.
[5] R.Albert, A.L. Barebasi, “Statistical mechanics of networks,” Rev Mod. Phys.74, pp.47-97, 2002.
[6] D.J.Watts, S.H.Strogatz, “Collective dynamics of 'small-world' networks,” Nature 393, pp.440-442, 1998.
[7] J. Zhou, J.A. Lu, J. Lu, “Pinning adaptive synchronization of a general complex dynamical network,” Automatica 44, pp.996-1003, 2008.
[8] W. Yu, G. Chen, J. Lü, “On pinning synchronization of complex dynamical networks,” Automatica 45, pp.429-435, 2009.
[9] L. Xiang, J.J.H. Zhu, “On pinning synchronization of general coupled networks,” Nonlinear Dynamics, 2010.
[10] S. Cai, Q. He, J. Hao, Z. Liu, “Exponential synchronization of complex networks with nonidentical time-delayed dynamical nodes, Physics Letters A 374, pp.2539-2550, 2010.
[11] Q. Song, J. Cao, F. Liu, “Synchronization of complex dynamical networks with nonidentical nodes,” Physics Letters A 374, pp.544-551, 2010.
[12] G. Solis-Perales, E. Ruiz-Velazquez, D. Valle-Rodriguez, “Synchronization in complex networks with distinct chaotic nodes,” Commun. Nonlinear Sci. Numer. Simulat. 14, pp.2528-2535, 2009.
[13] L. Wang, H.P. Dai, H. Dong, Y.Y.Cao, Y.X. Sun, “Adaptive synchronization of weighted complex dynamical networks through pinning,” Eur. Phys. J. B 61, pp.335-342, 2008.
[14] H. Tanga, L. Chena, J. Lua, C.K. Tse, “Adaptive synchronization between two complex networks with nonidentical topological structures,” Physica A 387, pp.5623-5630, 2008.
[15] S. Zheng, Q. Bi, G. Cai, “Adaptive projective synchronization in complex networks with time-varying coupling delay,” Physics Letters A 373, pp.1553-1559, 2009.
[16] D. Xu, Z. Su, “Synchronization criterions and pinning control of general complex networks with time delay,” Applied Mathematics and Computation 215, pp.1593-1608, 2009.
[17] E.N. Lorenz, “Deterministic nonperiodic flow,” J. Atmos. Sci. 20, pp.130-141, 1963.
[18] G. Chen, T. Ueta, Another chaotic attractor, Int. J. Bifurcation and Chaos 9, pp.1465-1466, 1999.
[19] J. Lu, G. Chen, “A new chaotic attractor coined,” Int. J. Bifurcation and Chaos 12, pp.659-661, 2002.
[20] H.K. Chen, C.I. Lee, “Anti-control of chaos in rigid body motion, Chaos, Solitons Fractals 21, pp.957-965, 2004.
[21] R. Genesio, A Tesi, “A harmonic balance methods for the analysis of chaotic dynamics in nonlinear systems,” Automatica 28, pp.531-548, 1992.

저 자 소 개

윤 한 오(정회원)
1981년 경북대학교 전자공학과 학사 졸업
1987년 경북대학교 대학원 전자공학과 석사 졸업
1992년 경북대학교 대학원 전자공학과 박사 졸업
1983년 8월~1985년 9월 삼성전자 시스템개발부 연구원
1992년~현재 구미대학교 컴퓨터정보전자과 교수
<주관심분야 : 견실제어, 적응제어, 시스템제어>