COMPLETE SYNCHRONIZATION OF HYPERCHAOTIC XU AND HYPERCHAOTIC LÜ SYSTEMS VIA ACTIVE CONTROL

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ABSTRACT

This paper deploys active control for achieving complete synchronization of hyperchaotic Xu (2009) and hyperchaotic Lü (2006) systems. Specifically, this paper derives complete synchronization results for identical hyperchaotic Xu systems, identical hyperchaotic Lü systems and non-identical hyperchaotic Xu and Lü systems. The complete synchronization results have been proved using Lyapunov stability theory. Numerical simulations have been shown to validate and demonstrate the effectiveness of the complete synchronization results derived in this paper.

KEYWORDS

Active Control, Synchronization, Hyperchaos, Hyperchaotic Xu System, Hyperchaotic Lü System.

1. INTRODUCTION

For the last few decades, chaos theory has been received critical investigations in a variety of fields including physical systems [1-2], chemical systems [3], ecological systems [4], secure communications [5-6], etc.

If we call a particular chaotic system as the *master* system and another chaotic system as the *slave* system, then the idea of complete chaos synchronization is to use the output of the master system to control the slave system so that the states of the slave system track the states of the master system asymptotically.

In the last two decades, a variety of schemes have been derived for chaos synchronization such as PC method [7], OGY method [8], active control [9-13], adaptive control [14-17], backstepping design [18-20], sampled-data feedback [21], sliding mode control [22-26], etc.

Hyperchaotic system is usually defined as a chaotic system having at least two positive Lyapunov exponents, implying that its dynamics can be extended in several directions simultaneously. Thus, hyperchaotic systems have more complex dynamical behaviour which can be used to improve the security of a chaotic communication system [27].

In this paper, we use active control method to derive new results for the complete chaos synchronization of identical hyperchaotic Xu systems ([28], 2009), identical hyperchaotic Lü systems ([29], 2006) and non-identical hyperchaotic Bao and hyperchaotic Xu systems. The complete synchronization results derived in this paper have been used using Lyapunov stability theory [30].

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2. PROBLEM STATEMENT AND OUR METHODOLOGY

As the *master* system, we take the chaotic system described by

$$\dot{x} = Ax + f(x), \tag{1}$$

where $x \in R^n$ is the state vector, A is the $n \times n$ matrix of system parameters and $f : R^n \to R^n$ is the nonlinear part of the system.

As the *slave* system, we take the chaotic system described by

$$\dot{y} = By + g(y) + u, \tag{2}$$

where $y \in R^n$ is the state of the slave system, B is the $n \times n$ matrix of system parameters, $g : R^n \to R^n$ is the nonlinear part of the system and u is the active controller to be designed.

If $A = B$ and $f = g$, then x and y are the states of two *identical* chaotic systems. If $A \neq B$ or $f \neq g$, then x and y are the states of two *different* chaotic systems.

For the complete chaos synchronization of the chaotic systems (1) and (2) using active control, we define the *synchronization error* as

$$e = y - x, \tag{3}$$

From (1), (2) and (3), the error dynamics is obtained as

$$\dot{e} = By - Ax + g(y) - f(x) + u \tag{4}$$

Thus, the complete synchronization problem is to determine a feedback controller u so that

$$\lim_{t \to \infty} \| e(t) \| = 0, \quad \text{for all } e(0) \in R^n \tag{5}$$

Next, we consider a candidate Lyapunov function

$$V(e) = e^T P e, \tag{6}$$

where P is a positive definite matrix. Note that $V : R^n \to R$ is a positive definite function by construction.

If we determine a feedback controller u so that

$$\dot{V}(e) = -e^T Q e, \tag{7}$$

where Q is a positive definite matrix, then $\dot{V} : R^n \to R$ is a negative definite function.

Thus, by Lyapunov stability theory [25], the error dynamics (4) is globally exponentially stable. Hence, the states of the master system (1) and slave system (2) are completely synchronized.

3. Systems Description

In this section, we give details of the hyperchaotic systems discussed in this paper.

The hyperchaotic Xu system ([28], 2009) is described by the 4D dynamics

$$\begin{aligned}
\dot{x}_1 &= a(x_2 - x_1) + x_4 \\
\dot{x}_2 &= bx_1 + \varepsilon x_1 x_3 \\
\dot{x}_3 &= -cx_3 - x_1 x_2 \\
\dot{x}_4 &= x_1 x_3 - dx_2
\end{aligned} \tag{8}$$

where x_1, x_2, x_3, x_4 are the states and a, b, c, d, ε are positive constants.

The system (8) exhibits hyperchaotic behaviour when the parameter values are chosen as

$$a = 10, \quad b = 40, \quad c = 2.5, \quad d = 2 \text{ and } \varepsilon = 16.$$

Figure 1 describes the hyperchaotic attractor of the hyperchaotic Xu system (8).

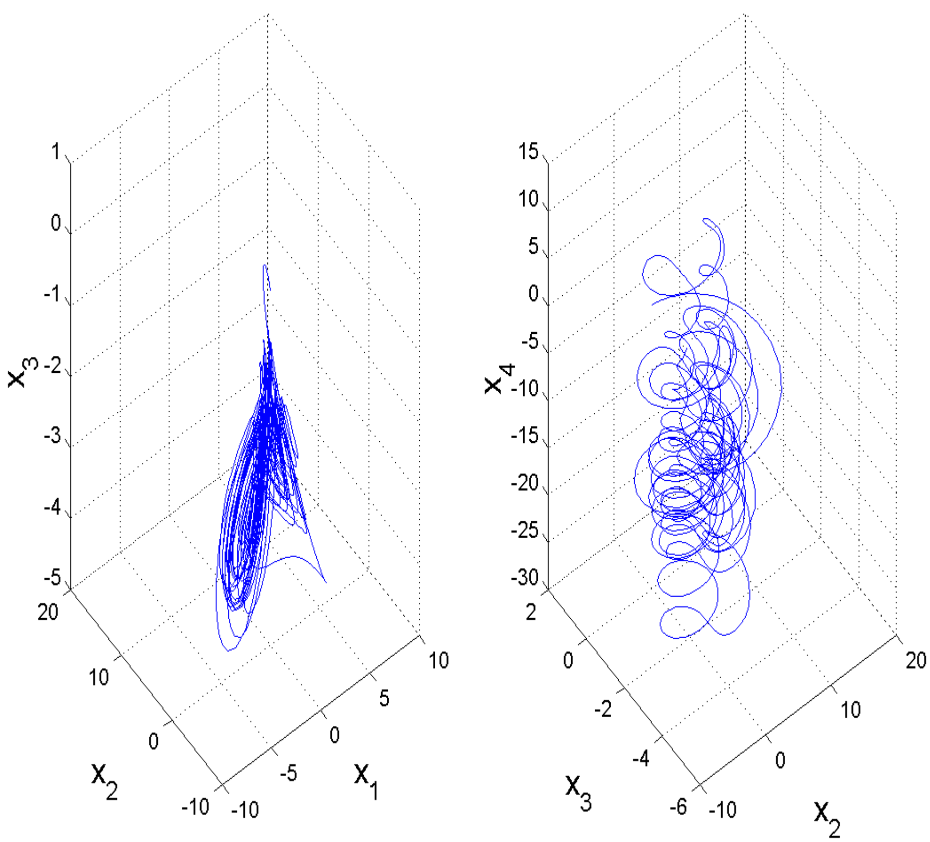

Figure 1. Hyperchaotic Attractor of the Hyperchaotic Xu System

The hyperchaotic Lü system ([29], 2006) is described by the 4D dynamics

$$\begin{aligned}
\dot{x}_1 &= \alpha(x_2 - x_1) + x_4 \\
\dot{x}_2 &= -x_1 x_3 + \gamma x_2 \\
\dot{x}_3 &= x_1 x_2 - \beta x_3 \\
\dot{x}_4 &= x_1 x_3 + \delta x_4
\end{aligned} \tag{9}$$

where x_1, x_2, x_3, x_4 are the states and a, b, c, d, ε are positive constants.

The system (9) exhibits hyperchaotic behaviour when the parameter values are chosen as

$$\alpha = 36, \quad \beta = 3, \quad \gamma = 20 \text{ and } \delta = 1.3.$$

Figure 2 describes the hyperchaotic attractor of the hyperchaotic Lü system (9).

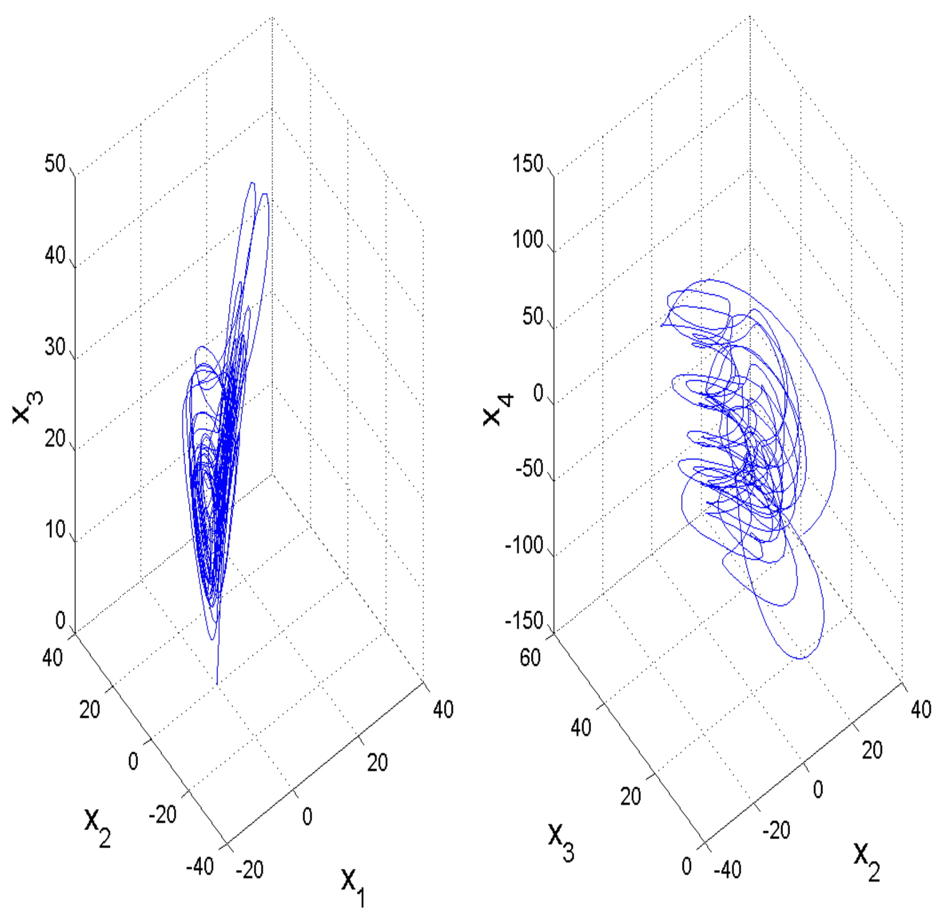

Figure 2. Hyperchaotic Attractor of the Hyperchaotic Lü System

4. SYNCHRONIZATION OF IDENTICAL HYPERCHAOTIC XU SYSTEMS

In this section, we apply active control method for the complete synchronization of identical hyperchaotic Xu systems (2009).

As the master system, we take the hyperchaotic Xu dynamics described by

$$\begin{aligned} \dot{x}_1 &= a(x_2 - x_1) + x_4 \\ \dot{x}_2 &= bx_1 + \varepsilon x_1 x_3 \\ \dot{x}_3 &= -cx_3 - x_1 x_2 \\ \dot{x}_4 &= x_1 x_3 - dx_2 \end{aligned} \tag{10}$$

where x_1, x_2, x_3, x_4 are the state variables and a, b, c, d, ε are positive constants.

As the slave system, we take the controlled hyperchaotic Xu dynamics described by

$$\begin{aligned} \dot{y}_1 &= a(y_2 - y_1) + y_4 + u_1 \\ \dot{y}_2 &= by_1 + \varepsilon y_1 y_3 + u_2 \\ \dot{y}_3 &= -cy_3 - y_1 y_2 + u_3 \\ \dot{y}_4 &= y_1 y_3 - dy_2 + u_4 \end{aligned} \tag{11}$$

where y_1, y_2, y_3, y_4 are the state variables and u_1, u_2, u_3, u_4 are the active controls.

The synchronization error is defined as

$$e_1 = y_1 - x_1,\ e_2 = y_2 - x_2,\ e_3 = y_3 - x_3,\ e_4 = y_4 - x_4 \tag{12}$$

A simple calculation gives the error dynamics

$$\begin{aligned} \dot{e}_1 &= a(e_2 - e_1) + e_4 + u_1 \\ \dot{e}_2 &= be_1 + \varepsilon(y_1 y_3 - x_1 x_3) + u_2 \\ \dot{e}_3 &= -ce_3 - y_1 y_2 + x_1 x_2 + u_3 \\ \dot{e}_4 &= y_1 y_3 - x_1 x_3 - de_2 + u_4 \end{aligned} \tag{13}$$

We consider the active nonlinear controller defined by

$$\begin{aligned} u_1 &= -a(e_2 - e_1) - e_4 - k_1 e_1 \\ u_2 &= -be_1 - \varepsilon(y_1 y_3 - x_1 x_3) - k_2 e_2 \\ u_3 &= ce_3 + y_1 y_2 - x_1 x_2 - k_3 e_3 \\ u_4 &= -y_1 y_3 + x_1 x_3 + de_2 - k_4 e_4 \end{aligned} \tag{14}$$

where the gains k_1, k_2, k_3, k_4 are positive constants.

Substitution of (14) into (13) yields the linear error dynamics

$$\dot{e}_1 = -k_1 e_1, \quad \dot{e}_2 = -k_2 e_2, \quad \dot{e}_3 = -k_3 e_3, \quad \dot{e}_4 = -k_4 e_4 \tag{15}$$

Theorem 4.1. *The identical hyperchaotic Xu systems (10) and (11) are globally and exponentially synchronized with the active nonlinear controller (14), where the gains* $k_i, \ (i = 1,2,3,4)$ *are positive constants.*

Proof. Consider the quadratic Lyapunov function defined by

$$V(e) = \frac{1}{2} e^T e = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2 + e_4^2\right), \tag{16}$$

which is a positive definite function on R^4.

Differentiating (16) along the trajectories of the error system (15), we get

$$\dot{V}(e) = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 - k_4 e_4^2, \tag{17}$$

which is a negative definite function on R^4 since k_1, k_2, k_3, k_4 are positive constants.

Thus, by Lyapunov stability theory [30], the error dynamics (15) is globally exponentially stable. ■

Numerical Simulations

For the numerical simulations, the fourth order Runge-Kutta method with initial time-step $h = 10^{-8}$ is used to solve the two systems (10) and (11) with the active controller (14). We take the gains as $k_i = 5$ for $i = 1,2,3,4.$

The parameters of the identical hyperchaotic Xu systems (10) and (11) are selected as

$$a = 10, \quad b = 40, \quad c = 2.5, \quad d = 2 \quad \text{and} \quad \varepsilon = 16.$$

The initial values for the master system (10) are taken as

$$x_1(0) = 5, \quad x_2(0) = -6, \quad x_3(0) = 12, \quad x_4(0) = -15$$

and the initial values for the slave system (11) are taken as

$$y_1(0) = -14, \quad y_2(0) = 8, \quad y_3(0) = 18, \quad y_4(0) = 16$$

Figure 3 shows the complete synchronization of the identical hyperchaotic Xu systems.

Figure 4 shows the time-history of the synchronization error e_1, e_2, e_3, e_4.

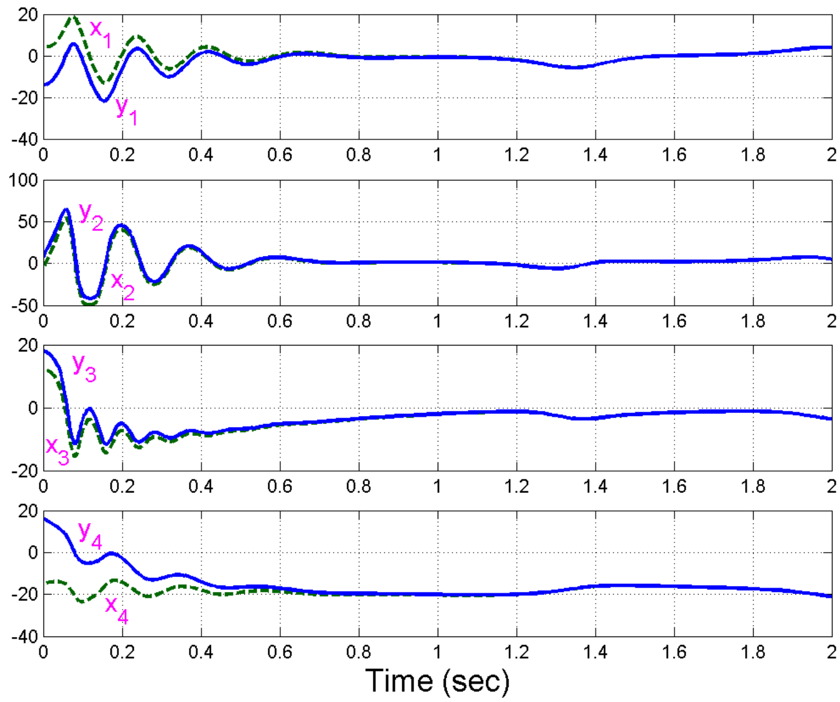

Figure 3. Synchronization of Identical Hyperchaotic Xu Systems

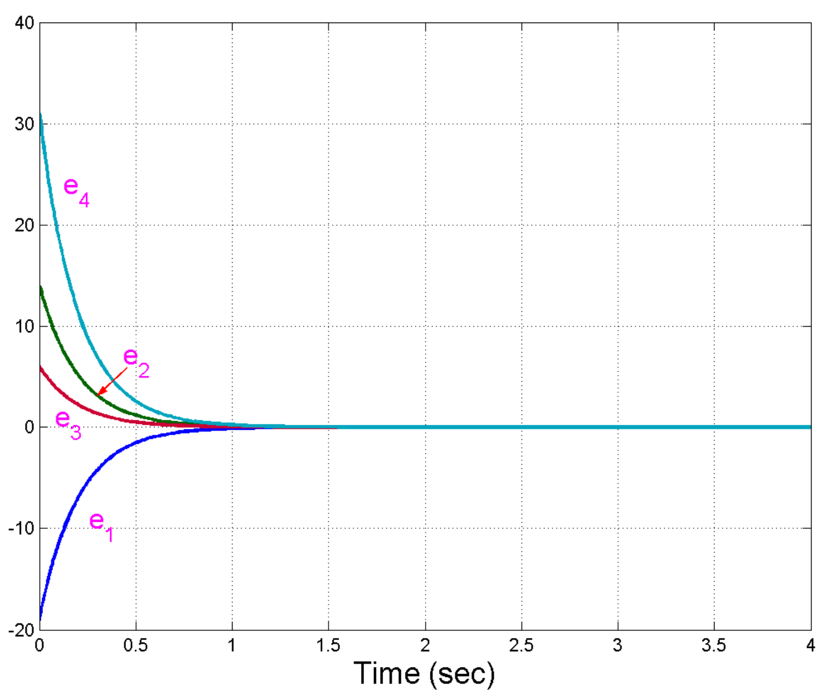

Figure 4. Time History of the Synchronization Error e_1, e_2, e_3, e_4

5. SYNCHRONIZATION OF IDENTICAL HYPERCHAOTIC LÜ SYSTEMS

In this section, we apply active control method for the complete synchronization of identical hyperchaotic Lü systems (2006).

As the master system, we take the hyperchaotic Lü dynamics described by

$$\begin{aligned} \dot{x}_1 &= \alpha(x_2 - x_1) + x_4 \\ \dot{x}_2 &= -x_1 x_3 + \gamma x_2 \\ \dot{x}_3 &= x_1 x_2 - \beta x_3 \\ \dot{x}_4 &= x_1 x_3 + \delta x_4 \end{aligned} \tag{18}$$

where x_1, x_2, x_3, x_4 are the state variables and $\alpha, \beta, \gamma, \delta$ are positive constants.

As the slave system, we take the controlled hyperchaotic Lü dynamics described by

$$\begin{aligned} \dot{y}_1 &= \alpha(y_2 - y_1) + y_4 + u_1 \\ \dot{y}_2 &= -y_1 y_3 + \gamma y_2 + u_2 \\ \dot{y}_3 &= y_1 y_2 - \beta y_3 + u_3 \\ \dot{y}_4 &= y_1 y_3 + \delta y_4 + u_4 \end{aligned} \tag{19}$$

where y_1, y_2, y_3, y_4 are the state variables and u_1, u_2, u_3, u_4 are the active controls.

The synchronization error is defined as

$$e_1 = y_1 - x_1,\; e_2 = y_2 - x_2,\; e_3 = y_3 - x_3,\; e_4 = y_4 - x_4 \tag{20}$$

A simple calculation gives the error dynamics

$$\begin{aligned} \dot{e}_1 &= \alpha(e_2 - e_1) + e_4 + u_1 \\ \dot{e}_2 &= \gamma e_2 + y_1 y_3 - x_1 x_3 + u_2 \\ \dot{e}_3 &= -\beta e_3 - y_1 y_2 + x_1 x_2 + u_3 \\ \dot{e}_4 &= \delta e_4 + y_1 y_3 - x_1 x_3 + u_4 \end{aligned} \tag{21}$$

We consider the active nonlinear controller defined by

$$\begin{aligned} u_1 &= -\alpha(e_2 - e_1) - e_4 - k_1 e_1 \\ u_2 &= -\gamma e_2 + y_1 y_3 - x_1 x_3 - k_2 e_2 \\ u_3 &= \beta e_3 - y_1 y_2 + x_1 x_2 - k_3 e_3 \\ u_4 &= -\delta e_4 - y_1 y_3 + x_1 x_3 + d e_2 - k_4 e_4 \end{aligned} \tag{22}$$

where the gains k_1, k_2, k_3, k_4 are positive constants.

Substitution of (22) into (21) yields the linear error dynamics

$$\dot{e}_1 = -k_1 e_1, \quad \dot{e}_2 = -k_2 e_2, \quad \dot{e}_3 = -k_3 e_3, \quad \dot{e}_4 = -k_4 e_4 \tag{23}$$

Theorem 5.1. *The identical hyperchaotic Lü systems (18) and (19) are globally and exponentially synchronized with the active nonlinear controller (22), where the gains* $k_i, \ (i = 1, 2, 3, 4)$ *are positive constants.*

Proof. Consider the quadratic Lyapunov function defined by

$$V(e) = \frac{1}{2} e^T e = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2 + e_4^2\right), \tag{24}$$

which is a positive definite function on R^4.

Differentiating (24) along the trajectories of the error system (23), we get

$$\dot{V}(e) = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 - k_4 e_4^2, \tag{25}$$

which is a negative definite function on R^4 since k_1, k_2, k_3, k_4 are positive constants.

Thus, by Lyapunov stability theory [30], the error dynamics (23) is globally exponentially stable. ■

Numerical Simulations

For the numerical simulations, the fourth order Runge-Kutta method with initial time-step $h = 10^{-8}$ is used to solve the two systems (18) and (19) with the active controller (22). We take the gains as $k_i = 5$ for $i = 1, 2, 3, 4$.

The parameters of the identical hyperchaotic Lü systems (18) and (19) are selected as

$$\alpha = 36, \quad \beta = 3, \quad \gamma = 20 \quad \text{and} \quad \delta = 1.3.$$

The initial values for the master system (18) are taken as

$$x_1(0) = 8, \quad x_2(0) = 26, \quad x_3(0) = -15, \quad x_4(0) = -9$$

and the initial values for the slave system (19) are taken as

$$y_1(0) = -4, \quad y_2(0) = 18, \quad y_3(0) = -8, \quad y_4(0) = 19$$

Figure 5 shows the complete synchronization of the identical hyperchaotic Lü systems.

Figure 6 shows the time-history of the synchronization error e_1, e_2, e_3, e_4.

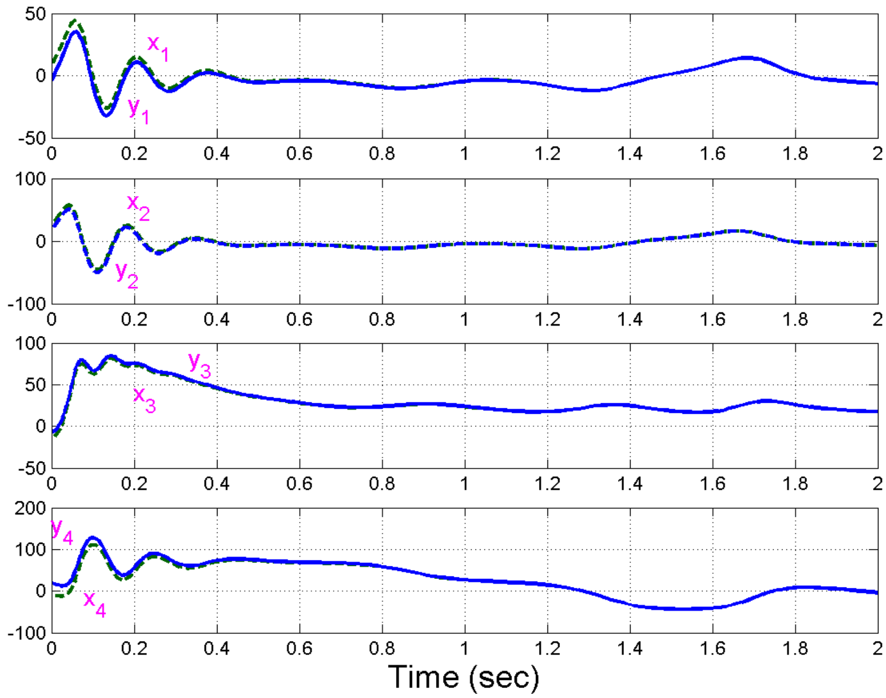

Figure 5. Synchronization of Identical Hyperchaotic Lü Systems

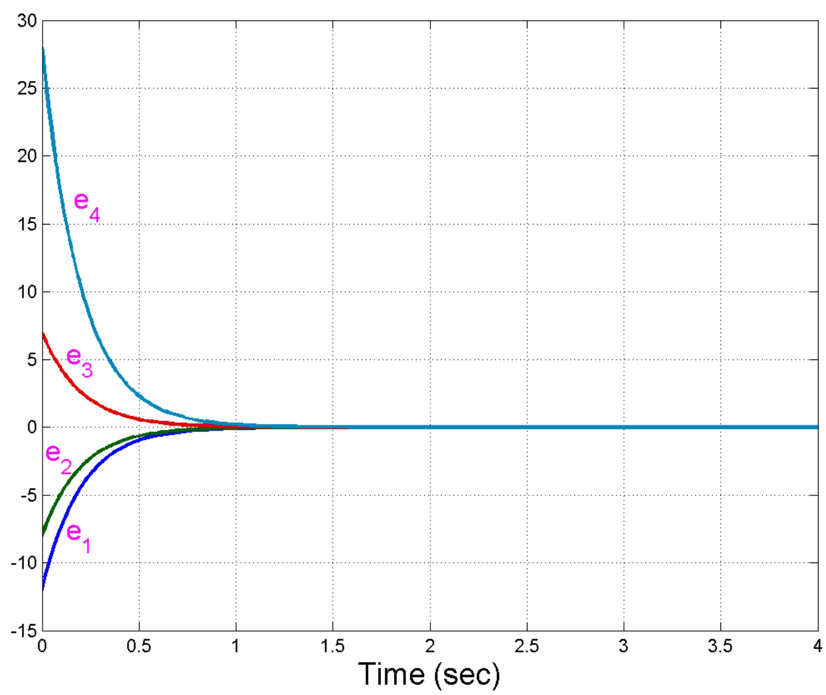

Figure 6. Time History of the Synchronization Error e_1, e_2, e_3, e_4

6. Synchronization of Non-Identical Hyperchaotic Xu and Hyperchaotic Lü Systems

In this section, we consider the global chaos synchronization of non-identical hyperchaotic Xu system ([28], 2009) and hyperchaotic Lü system ([29], 2006).

As the master system, we take the hyperchaotic Xu dynamics described by

$$\begin{aligned} \dot{x}_1 &= a(x_2 - x_1) + x_4 \\ \dot{x}_2 &= bx_1 + \varepsilon x_1 x_3 \\ \dot{x}_3 &= -cx_3 - x_1 x_2 \\ \dot{x}_4 &= x_1 x_3 - dx_2 \end{aligned} \tag{26}$$

where x_1, x_2, x_3, x_4 are the state variables and a, b, c, d are positive constants.

As the slave system, we take the controlled hyperchaotic Lü dynamics described by

$$\begin{aligned} \dot{y}_1 &= \alpha(y_2 - y_1) + y_4 + u_1 \\ \dot{y}_2 &= -y_1 y_3 + \gamma y_2 + u_2 \\ \dot{y}_3 &= y_1 y_2 - \beta y_3 + u_3 \\ \dot{y}_4 &= y_1 y_3 + \delta y_4 + u_4 \end{aligned} \tag{27}$$

where y_1, y_2, y_3, y_4 are the state variables, $\alpha, \beta, \gamma, \delta$ are positive constants and u_1, u_2, u_3, u_4 are the active controls.

The synchronization error is defined as

$$e_1 = y_1 - x_1,\; e_2 = y_2 - x_2,\; e_3 = y_3 - x_3,\; e_4 = y_4 - x_4 \tag{28}$$

A simple calculation gives the error dynamics

$$\begin{aligned} \dot{e}_1 &= \alpha(e_2 - e_1) + (\alpha - a)(x_2 - x_1) - e_4 + u_1 \\ \dot{e}_2 &= \gamma y_2 - bx_1 - y_1 y_3 - \varepsilon x_1 x_3 + u_2 \\ \dot{e}_3 &= -\beta e_3 + (c - \beta)x_3 + y_1 y_2 + x_1 x_2 + u_3 \\ \dot{e}_4 &= \delta y_4 + dx_2 + y_1 y_3 - x_1 x_3 + u_4 \end{aligned} \tag{29}$$

We consider the active nonlinear controller defined by

$$\begin{aligned} u_1 &= -\alpha(e_2 - e_1) - (\alpha - a)(x_2 - x_1) + e_4 - k_1 e_1 \\ u_2 &= -\gamma y_2 + bx_1 + y_1 y_3 + \varepsilon x_1 x_3 - k_2 e_2 \\ u_3 &= \beta e_3 - (c - \beta)x_3 - y_1 y_2 - x_1 x_2 - k_3 e_3 \\ u_4 &= -\delta y_4 - dx_2 - y_1 y_3 + x_1 x_3 - k_4 e_4 \end{aligned} \tag{30}$$

where the gains k_1, k_2, k_3, k_4 are positive constants.

Substitution of (30) into (29) yields the linear error dynamics

$$\dot{e}_1 = -k_1 e_1, \;\; \dot{e}_2 = -k_2 e_2, \;\; \dot{e}_3 = -k_3 e_3, \;\; \dot{e}_4 = -k_4 e_4 \tag{31}$$

Theorem 6.1. *The hyperchaotic Xu system (26) and hyperchaotic Lü system (26) are globally and exponentially synchronized with the active nonlinear controller (30), where the gains* $k_i, \; (i = 1, 2, 3, 4)$ *are positive constants.*

Proof. Consider the quadratic Lyapunov function defined by

$$V(e) = \frac{1}{2} e^T e = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2 + e_4^2\right), \tag{32}$$

which is a positive definite function on R^4.

Differentiating (24) along the trajectories of the error system (23), we get

$$\dot{V}(e) = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 - k_4 e_4^2, \tag{33}$$

which is a negative definite function on R^4 since k_1, k_2, k_3, k_4 are positive constants.

Thus, by Lyapunov stability theory [30], the error dynamics (31) is globally exponentially stable. ■

Numerical Simulations

For the numerical simulations, the fourth order Runge-Kutta method with initial time-step $h = 10^{-8}$ is used to solve the two systems (26) and (27) with the active controller (22). We take the gains as $k_i = 5$ for $i = 1, 2, 3, 4.$

The parameters of the hyperchaotic Xu and hyperchaotic Lü systems are selected as

$$a = 10, \; b = 40, \; c = 2.5, \; d = 2, \; \varepsilon = 16, \; \alpha = 36, \; \beta = 3, \; \gamma = 20, \; \delta = 1.3$$

The initial values for the master system (26) are taken as

$$x_1(0) = -12, \;\; x_2(0) = 16, \;\; x_3(0) = 25, \;\; x_4(0) = -19$$

and the initial values for the slave system (27) are taken as

$$y_1(0) = 24, \;\; y_2(0) = 8, \;\; y_3(0) = -14, \;\; y_4(0) = 6$$

Figure 7 shows the complete synchronization of the hyperchaotic Xu and hyperchaotic Lü systems.

Figure 8 shows the time-history of the synchronization error $e_1, e_2, e_3, e_4.$

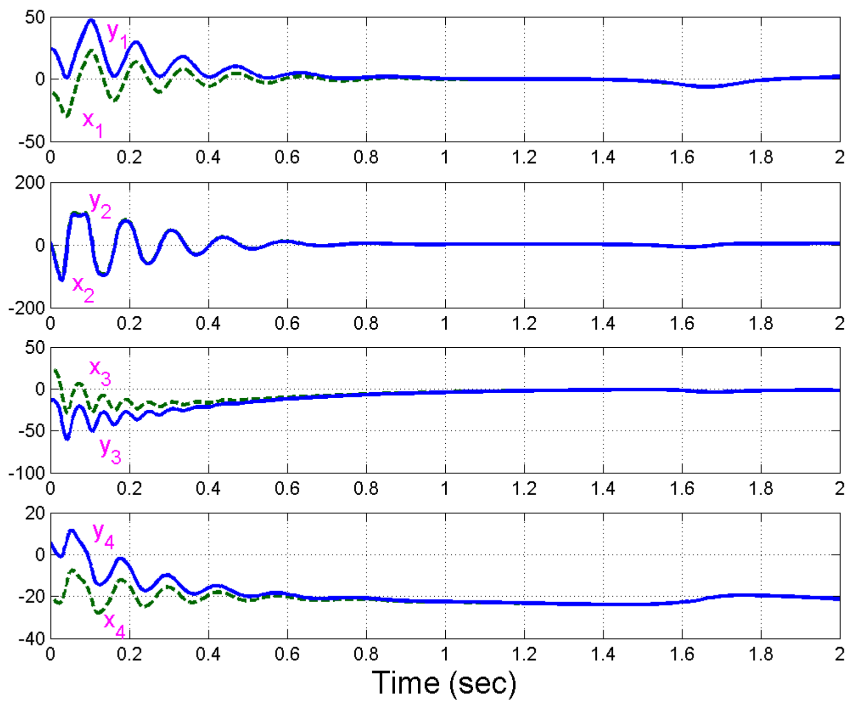

Figure 7. Synchronization of Hyperchaotic Xu and Hyperchaotic Lü Systems

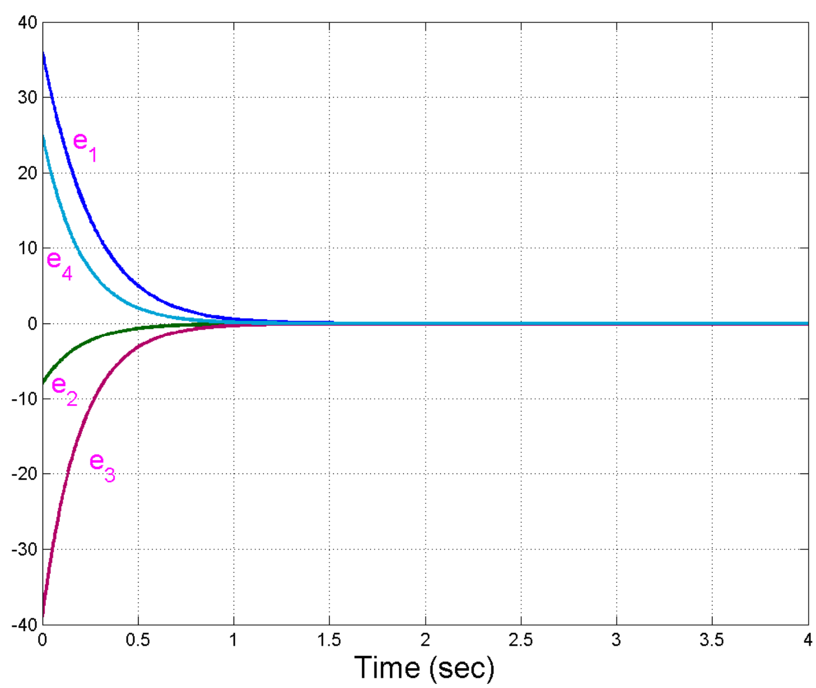

Figure 8. Time History of the Synchronization Error e_1, e_2, e_3, e_4

7. CONCLUSIONS

Using the active control method, we have derived new results for the complete synchronization of the identical hyperchaotic Xu systems (2009), identical hyperchaotic Lü systems (2006) and non-identical hyperchaotic Xu and hyperchaotic Lü systems. The complete synchronization results derived in this paper have been proved using Lyapunov stability theory. Numerical simulation results have been shown to demonstrate the complete synchronization results derived in this paper.

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