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Hybrid Synchronization of Identical Hyperchaotic Systems via Novel Sliding Control with Application to Hyperchaotic Vaidyanathan-Volos System

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ABSTRACT

First, this paper proposes a general procedure for the hybrid synchronization of identical hyperchaotic systems using novel sliding mode control. The general result derived using novel sliding mode control method is established via Lyapunov stability theory. As an application of the general result, the problem of hybrid synchronization of identical hyperchaotic Vaidyanathan-Volos systems (2016) is studied and a new sliding mode controller is derived. Numerical simulations with MATLAB have been shown to illustrate all the main results derived in this work.

Keywords: Hyperchaos, hyperchaos synchronization, hybrid synchronization, sliding mode control.

1. INTRODUCTION

A *chaotic system* is commonly defined as a nonlinear dissipative dynamical system that is highly sensitive to even small perturbations in its initial conditions [1]. In other words, a chaotic system is a nonlinear dynamical system with at least one positive Lyapunov exponent. Some paradigms of chaotic systems can be listed as Arneodo system [4], Sprott systems [5], Chen system [6], Lü-Chen system [7], Liu system [8], Cai system [9], Tigan system [10], etc.

In the last two decades, many new chaotic systems have been also discovered like Li system [11], Sundarapandian systems [12-13], Vaidyanathan systems [14-33], Pehlivan systems [34-35], Pham systems [36-37], Jafari system [38], etc.

Hyperchaotic systems are the chaotic systems with more than one positive Lyapunov exponent. They have important applications in control and communication engineering. Some recently discovered 4-D hyperchaotic systems are hyperchaotic Vaidyanathan systems [39-40], hyperchaotic Vaidyanathan-Azar system [41], hyperchaotic Sampath system [42], etc,

Chaos theory has several applications in a variety of fields such as oscillators [43-44], chemical reactors [45-58], biology [59-80], ecology [81-82], neural networks [83-84], robotics [85-86], memristors [87-89], fuzzy systems [90-91], etc.

The problem of control of a chaotic system is to find a state feedback control law to stabilize a chaotic system around its unstable equilibrium [92-93]. Some popular methods for chaos control are active control [94-98], adaptive control [99-100], sliding mode control [101-103], etc.

If a particular chaotic system is called the *master* or *drive* system and another chaotic system is called the *slave* or *response* system, then the idea of hybrid synchronization is to completely synchronize one part

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of the systems (namely, the odd states) and anti-synchronize the other part of the systems (namely, the even states) so that both complete and anti-synchronization persist in the process of synchronization of the master and slave systems.

The synchronization of chaotic systems has applications in secure communications [104-107], cryptosystems [108-109], encryption [110-111], etc.

The chaos synchronization problem has been paid great attention in the literature and a variety of impressive approaches have been proposed. Since the pioneering work by Pecora and Carroll [112-113] for the chaos synchronization problem, many different methods have been proposed in the control literature such as active control method [114-132], adaptive control method [133-149], sampled-data feedback control method [150-151], time-delay feedback approach [152], backstepping method [153-164], sliding mode control method [165-173], etc.

In this paper, new results have been derived for the hybrid synchronization of identical hyperchaotic systems using novel sliding control. The sliding mode control has advantages of low sensitivity to parameter variations in the plant and disturbances affecting the plant.

In Section 2, we describe the hybrid synchronization of identical hyperchaotic systems. In Section 3, we derive a general result for the hybrid synchronization of identical hyperchaotic systems using novel sliding mode control. In Section 4, we describe the hyperchaotic Vaidyanathan-Volos system ([42], 2016) and its qualitative properties. The phase portraits of the hyperchaotic Vaidyanathan-Volos system are described using MATLAB. In Section 5, we describe the sliding mode controller design for the hybrid synchronization of the hyperchaotic Vaidyanathan-Volos systems using novel sliding mode control and its numerical simulations using MATLAB. Section 6 contains a summary of the main results derived in this paper.

2. HYBRID SYNCHRONIZATION OF IDENTICAL HYPERCHAOTIC SYSTEMS

In this section, we provide a problem statement for the hybrid synchronization of identical hyperchaotic systems.

As the *master* or *drive* system, we consider the hyperchaotic system given by

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

In Eq. (1), $x \in R^n$ denotes the state of the system, A denotes the matrix of system parameters and φ contains the nonlinear parts of the system.

As the *slave* or *response* system, we take the controlled hyperchaotic system given by

$$\dot{y} = Ay + \varphi(y) + u \tag{2}$$

In Eq. (2), $y \in R^n$ denotes the state of the system and $u \in R^n$ is the control.

The hybrid synchronization error between the hyperchaotic systems (1) and (2) is defined as

$$e_i = \begin{cases} y_i - x_i & \text{if} \quad i \text{ is odd} \\ y_i + x_i & \text{if} \quad i \text{ is even} \end{cases} \tag{3}$$

A simple calculation yields the error dynamics as

$$\dot{e} = Ae + \eta(x, y) + u \tag{4}$$

Thus, the hybrid synchronization problem for the hyperchaotic systems (1) and (2) can be defined as follows: Find a controller u so as to render the hybrid synchronization error $e(t)$ to be globally asymptotically stable for all values of $e(0) \in R^n$, *i.e.*

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

3. A NOVEL SLIDING CONTROLLER DESIGN

First, we set the design by setting the control as

$$u(t) = -\eta(x,y) + Bv(t) \tag{6}$$

In Eq. (6), $B\in R^n$ is chosen such that (A, B) is completely controllable.

By substituting (6) into (4), we get the closed-loop error dynamics

$$\dot{e} = Ae + Bv \tag{7}$$

The system (7) is a linear time-variant control system with single input v.

We start the sliding controller design by defining the sliding variable as

$$s(e) = Ce = c_1e_1 + c_2e_2 + \cdots + c_ne_n, \tag{8}$$

where $C\in R^{1\times n}$ is a constant vector to be determined.

The *sliding manifold* is defined as the hyperplane

$$S = \left\{e\in R^n : s(e) = Ce = 0\right\}. \tag{9}$$

We shall assume that a sliding motion occurs on the hyperplane S.

In sliding mode, the following equations must be satisfied:

$$s \equiv 0 \text{ and } \dot{s} \equiv CAe + CBv = 0 \tag{10}$$

We assume that

$$CB \neq 0 \tag{11}$$

The sliding motion is influenced by the equivalent control derived from (10) as

$$v_{eq}(t) = -(CB)^{-1}CAe(t) \tag{12}$$

By substituting (12) into (7), we obtain the equivalent error dynamics in the sliding phase as

$$\dot{e} = Ae - (CB)^{-1}CAe = Ee, \tag{13}$$

where

$$E = [I - B(CB)^{-1}C]A \tag{14}$$

We note that E is independent of the control and has at most $(n-1)$ nonzero eigenvalues, depending on the chosen switching surface, while the associated eigenvectors belong to ker(C)

Since (A, B) is controllable, we can use sliding control theory to choose B and C so that E has any desired $(n-1)$ stable eigenvalues.

This shows that the dynamics in the sliding mode is globally asymptotically stable.

Finally, for the sliding controller design, we apply a *novel sliding control law*, viz.

$$\dot{s} = -ks - qs^2\text{sgn}(s) \tag{15}$$

In Eq. (15), sgn(.) denotes the sign function and the sliding mode control constants $k > 0$, $q > 0$ are found in such a way that the sliding condition is satisfied and that the sliding motion will occur.

By combining equations (10), (12) and (15), we finally obtain the sliding mode control (SMC) $v(t)$ as

$$v(t) = -(CB)^{-1}[C(kI + A)e + qs^2 \operatorname{sgn}(s)] \tag{16}$$

Next, we establish the main result of this section.

Theorem 1. The sliding mode controller law defined by (6) achieves global and asymptotic hybrid synchronization of the identical hyperchaotic systems (1) and (2) for all initial conditions $x(0), y(0) \in R^n$, where v is defined by the novel sliding control law (16), $B \in R^{n\times 1}$ is such that (A, B) is controllable, $C \in R^{1\times n}$ is such that $CB \neq 0$ and that the matrix E defined by (14) has $(n - 1)$ stable eigenvalues.

Proof. Upon substitution of the control laws (6) and (16) into the error dynamics (4), we get the closed-loop error dynamics as

$$\dot{e} = Ae - B(CB)^{-1}\left[C(kI + A)e + qs^2 \operatorname{sgn}(s)\right] \tag{17}$$

We shall show that the error system (17) is globally asymptotically stable by considering the quadratic Lyapunov function

$$V(e) = \frac{1}{2} s^2(e) \tag{18}$$

The sliding mode motion is characterized by the equations

$$s(e) = 0 \text{ and } \dot{s}(e) = 0 \tag{19}$$

By the choice of E, the dynamics in the sliding mode is globally asymptotically stable.

When $s(e) \neq 0,\ V(e) > 0.$

Also, when $s(e) \neq 0,$ differentiating V along the error dynamics (17) or the equivalent dynamics (15), we get

$$\dot{V}(e) = s\dot{s} = -ks^2 - qs^3 \operatorname{sgn}(s) < 0. \tag{20}$$

Hence, by Lyapunov stability theory [174], the error dynamics (17) is globally asymptotically stable for all $e(0) \in R^n$.

This completes the proof. ■

4. HYPERCHAOTIC VAIDYANATHAN-VOLOS SYSTEM

Hyperchaotic Vaidyanathan-Volos system ([42], 2016) is described by the 4-D dynamics

$$\begin{cases} \dot{x}_1 = a(x_2 - x_1) + x_4 \\ \dot{x}_2 = bx_1 - px_1x_3 + x_4 \\ \dot{x}_3 = x_1x_2 - cx_3 \\ \dot{x}_4 = -x_1 - x_2 \end{cases} \tag{21}$$

where x_1, x_2, x_3, x_4 are state variables and a, b, c, p are positive parameters of the system.

The Vaidyanathan-Volos system (21) exhibits a *hyperchaotic attractor* for the values

$$a = 12, \quad b = 36, \quad c = 5, \quad p = 12 \tag{22}$$

The Lyapunov exponents of the system (21) are numerically obtained with MATLAB as

$$L_1 = 1.0784, \quad L_2 = 0.1114, \quad L_3 = 0, \quad L_4 = -18.1714 \tag{23}$$

As there are two positive Lyapunov exponents in (23), the system (21) is hyperchaotic.

Since the sum of the Lyapunov exponents in (23) is negative, the hyperchaotic Vaidyanathan-Volos system is dissipative.

The Lyapunov dimension of the hyperchaotic Vaidyanathan-Volos system (21) is found as

$$D_L = \frac{L_1 + L_2 + L_3}{|L_4|} = 3.0655 \tag{24}$$

For simulations, the initial values of the Vaidyanathan-Volos system (21) are taken as

$$x_1(0) = 1.8, \quad x_2(0) = 1.6, \quad x_3(0) = 1.2, \quad x_4(0) = 1.4 \tag{25}$$

Figures 1-4 show the 3-D view of the hyperchaotic attractor of the Vaidyanathan-Volos system (21) in (x_1, x_2, x_3), (x_1, x_2, x_4), (x_1, x_3, x_4) and (x_2, x_3, x_4) spaces, respectively.

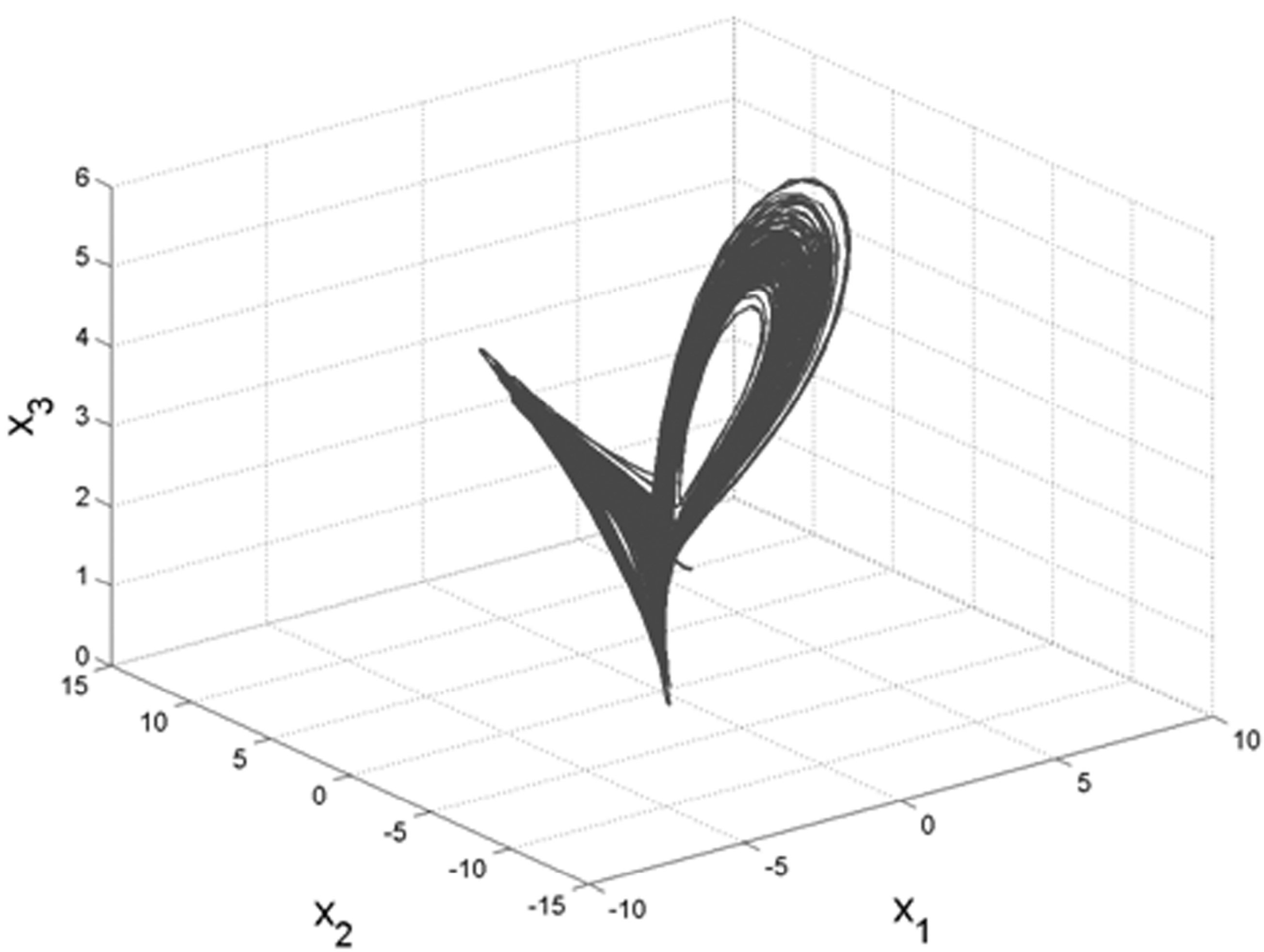

Figure 1: 3-D view of hyperchaotic Vaidyanathan-Volos system in (x_1, x_2, x_3) space

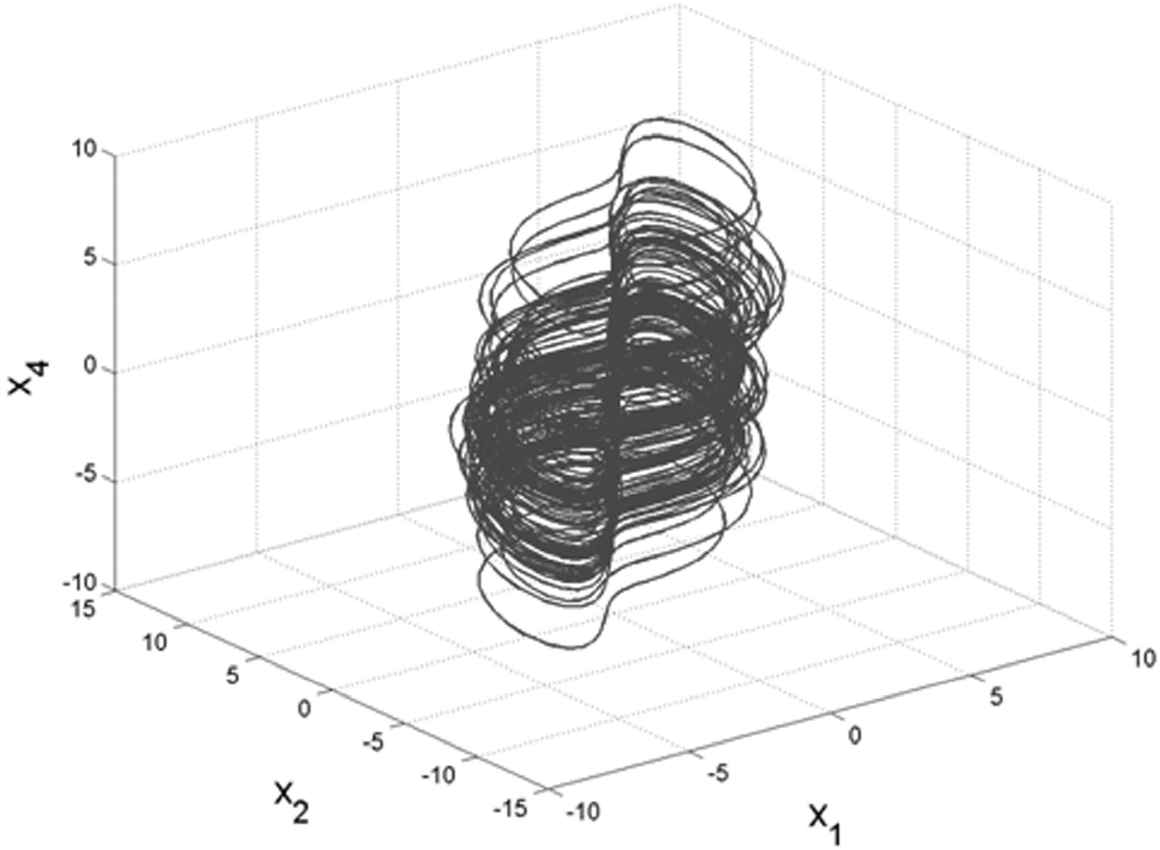

Figure 2: 3-D view of hyperchaotic Vaidyanathan-Volos system in (x_1, x_2, x_4) space

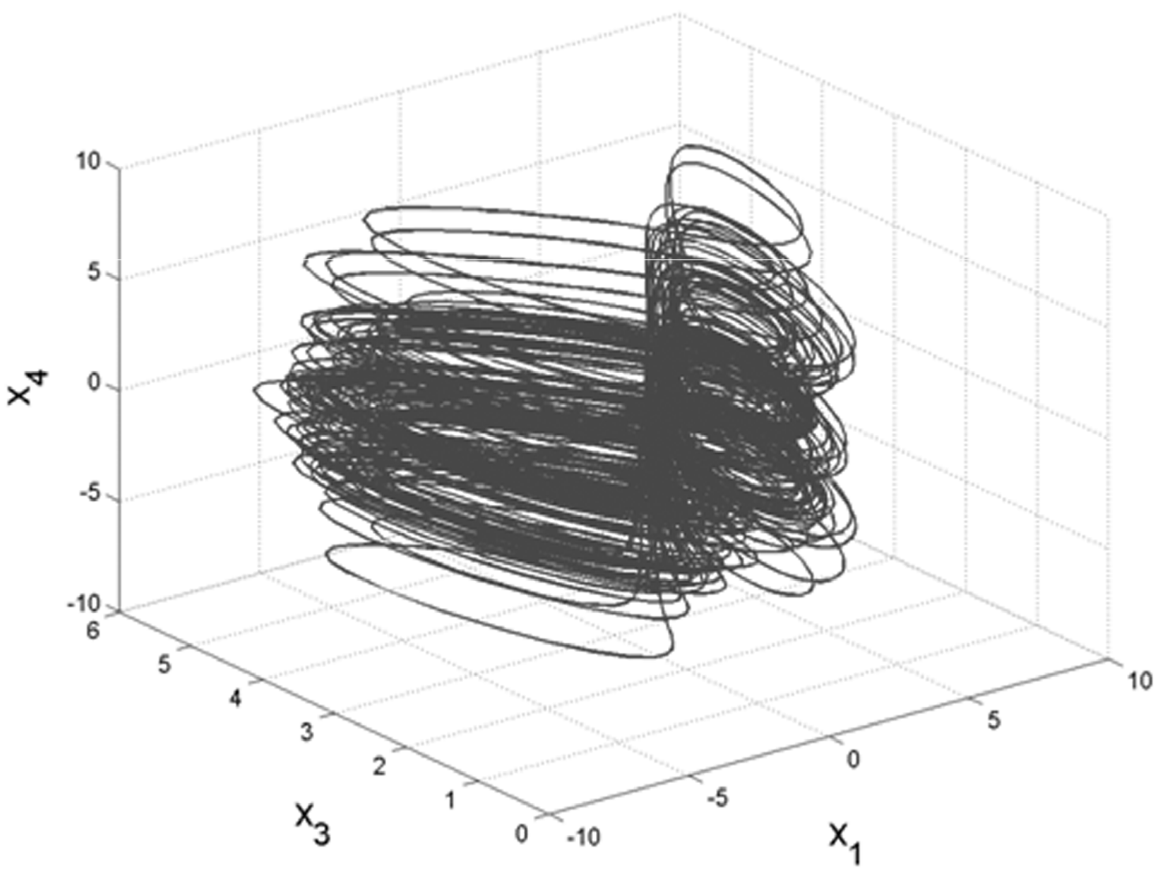

Figure 3: 3-D view of hyperchaotic Vaidyanathan-Volos system in (x_1, x_3, x_4) space

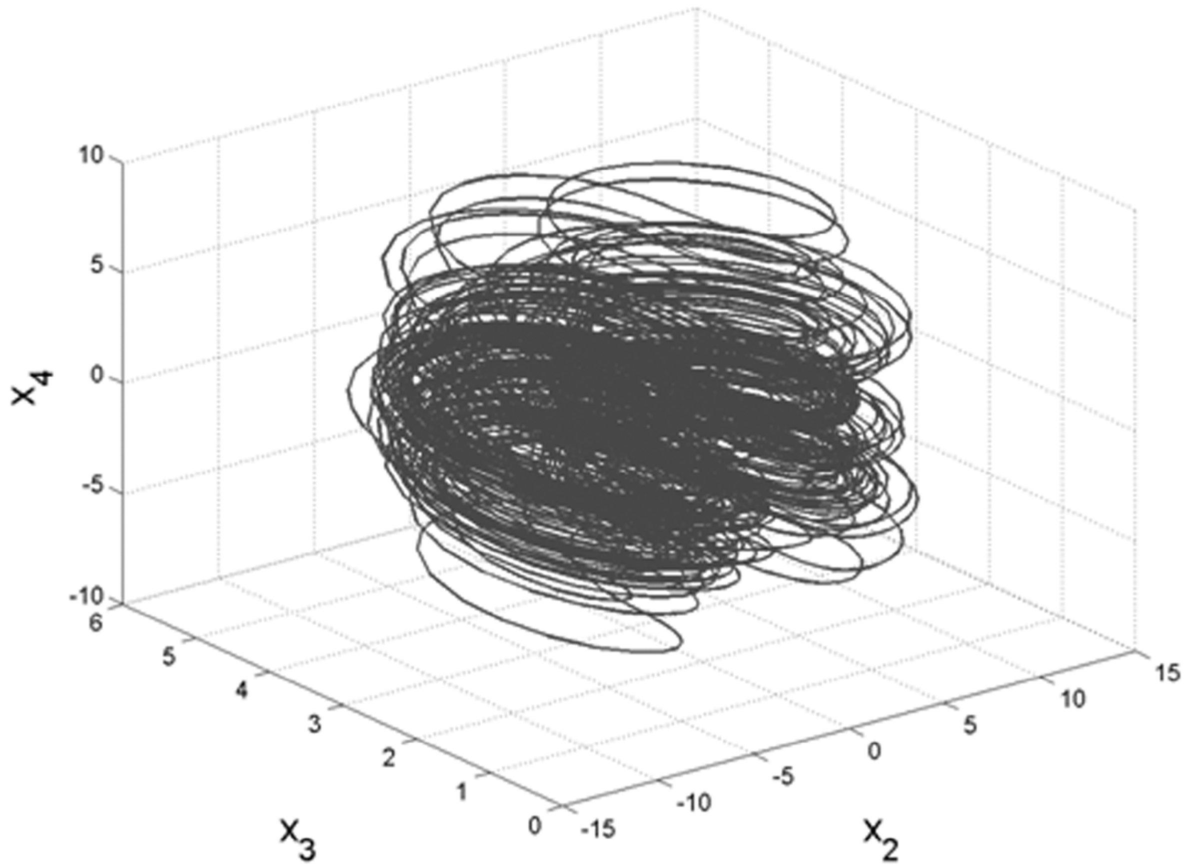

Figure 4: 3-D view of hyperchaotic Vaidyanathan-Volos system in (x_2, x_3, x_4) space

5. HYBRID SYNCHRONIZATION OF HYPERCHAOTIC VAIDYANATHAN-VOLOS SYSTEMS VIA NOVEL SLIDING CONTROL

In this section, we describe novel sliding mode control design for the hybrid synchronization of identical hyperchaotic Vaidyanathan-Volos systems.

As the master system, we consider the hyperchaotic Vaidyanathan-Volos system given by

$$\begin{cases} \dot{x}_1 = a(x_2 - x_1) + x_4 \\ \dot{x}_2 = bx_1 - px_1x_3 + x_4 \\ \dot{x}_3 = x_1x_2 - cx_3 \\ \dot{x}_4 = -x_1 - x_2 \end{cases} \tag{26}$$

where x_1, x_2, x_3, x_4 are state variables and a, b, c, d, p, q are positive parameters.

As the slave system, we consider the hyperchaotic Vaidyanathan-Volos system given by

$$\begin{cases} \dot{y}_1 = a(y_2 - y_1) + y_4 + u_1 \\ \dot{y}_2 = by_1 - py_1y_3 + y_4 + u_2 \\ \dot{y}_3 = y_1y_2 - cy_3 + u_3 \\ \dot{y}_4 = -y_1 - y_2 + u_4 \end{cases} \tag{27}$$

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

The hybrid synchronization error between the systems (26) and (27) is defined by

$$\begin{cases} e_1 = y_1 - x_1 \\ e_2 = y_2 + x_2 \\ e_3 = y_3 - x_3 \\ e_4 = y_4 + x_4 \end{cases} \tag{28}$$

Then the error dynamics is obtained as

$$\begin{cases} \dot{e}_1 = a(e_2 - e_1) + e_4 - 2ax_2 - 2x_4 + u_1 \\ \dot{e}_2 = be_1 + e_4 + 2bx_1 - p(y_1 y_3 + x_1 x_3) + u_2 \\ \dot{e}_3 = -ce_3 + y_1 y_2 - x_1 x_2 + u_3 \\ \dot{e}_4 = -e_1 - e_2 - 2x_1 + u_4 \end{cases} \tag{29}$$

In matrix form, we can write the error dynamics (29) as

$$\dot{e} = Ae + \eta(x, y) + u, \tag{30}$$

where

$$A = \begin{bmatrix} -a & a & 0 & 1 \\ b & 0 & 0 & 1 \\ 0 & 0 & -c & 0 \\ -1 & -1 & 0 & 0 \end{bmatrix}, \eta(x, y) = \begin{bmatrix} -2ax_2 - 2x_4 \\ 2bx_1 - p(y_1 y_3 + x_1 x_3) \\ y_1 y_2 - x_1 x_2 \\ -2x_1 \end{bmatrix}, u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \tag{31}$$

First, we set u as

$$u(t) = -\eta(x, y) + Bv(t), \tag{32}$$

where B is selected such that (A, B) is completely controllable.

We choose B as

$$B = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{33}$$

We choose the parameters of the Vaidyanathan-Volos systems as in the hyperchaotic case, *viz.*

$$a = 12, \quad b = 36, \quad c = 5, \quad p = 12 \tag{34}$$

The sliding mode variable is selected as

$$s = Ce = \begin{bmatrix} 60 & 40 & 10 & -50 \end{bmatrix} e = 60e_1 + 40e_2 + 10e_3 - 50e_4 \tag{35}$$

which renders the sliding motion globally asymptotically stable.

Next, we take the sliding mode gains as

$$k = 6 \text{ and } q = 0.2. \quad (36)$$

From Eq. (16) of Section 3, we obtain the novel sliding control v as

$$v = -18.8333e_1 - 16.8333e_2 - 0.1667e_3 + 3.3333e_4 - 0.0033s^2 \,\mathrm{sgn}(s) \quad (37)$$

As an application of Theorem 1 to the identical hyperchaotic Vaidyanathan-Volos systems, we obtain the following main result of this section.

Theorem 2. The identical hyperchaotic Vaidyanathan-Volos systems (26) and (27) are globally and asymptotically hybrid synchronized for all initial conditions $x(0), y(0) \in R^4$ with the sliding controller u defined by (32), where $\eta(x, y)$ and B are defined by (31) andis defined by (37). ■

For numerical simulation, we take the parameter values as in the hyperchaotic case, i.e.

$$a = 12, \quad b = 36, \quad c = 5, \quad p = 12$$

As an initial condition for the master system (25), we take

$$x_1(0) = 5.2, \quad x_2(0) = -2.3, \quad x_3(0) = 4.5, \quad x_4(0) = -7.7$$

As an initial condition for the slave system (26), we take

$$y_1(0) = 1.4, \quad y_2(0) = 5.8, \quad y_3(0) = -2.6, \quad y_4(0) = 8.4$$

Figures 5-8 depict the hybrid synchronization of the hyperchaotic Vaidyanathan-Volos systems.

Figure 9 depicts the time-history of the hybrid synchronization errors.

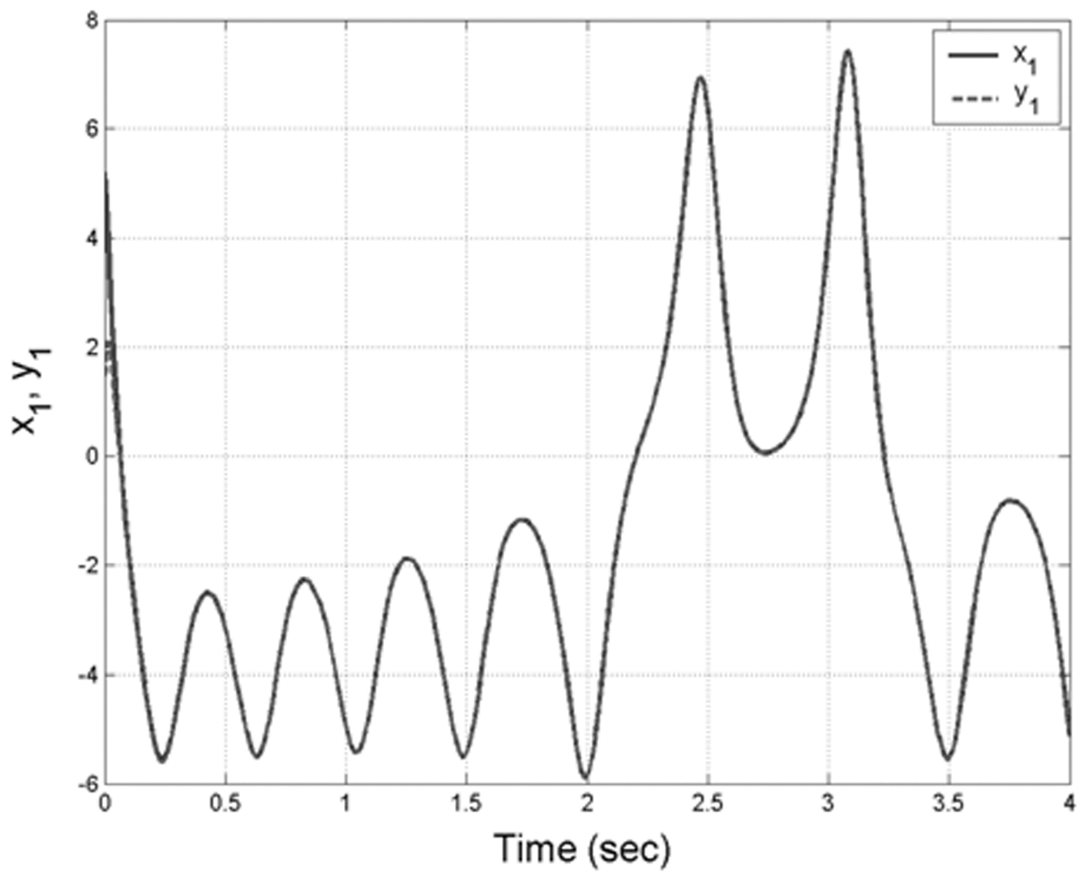

Figure 5: Hybrid synchronization of the states x_1 and y_1

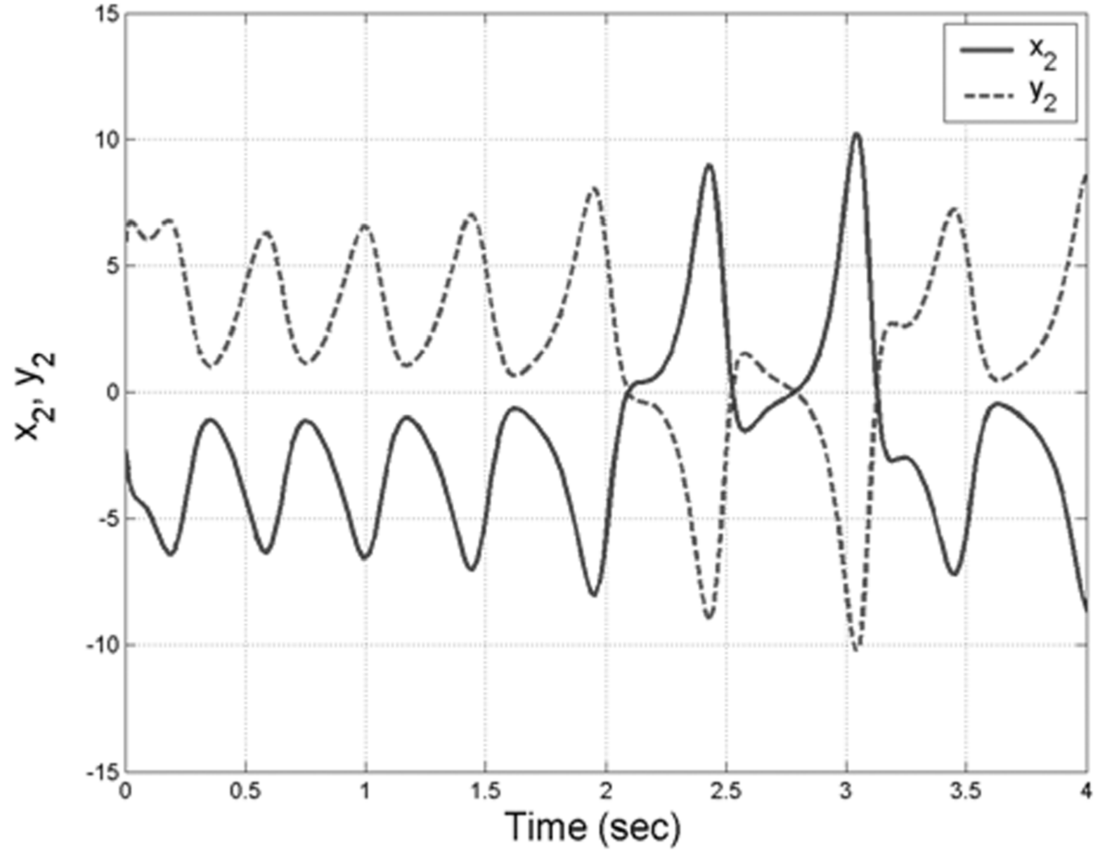

Figure 6: Hybrid synchronization of the states x_2 and y_2

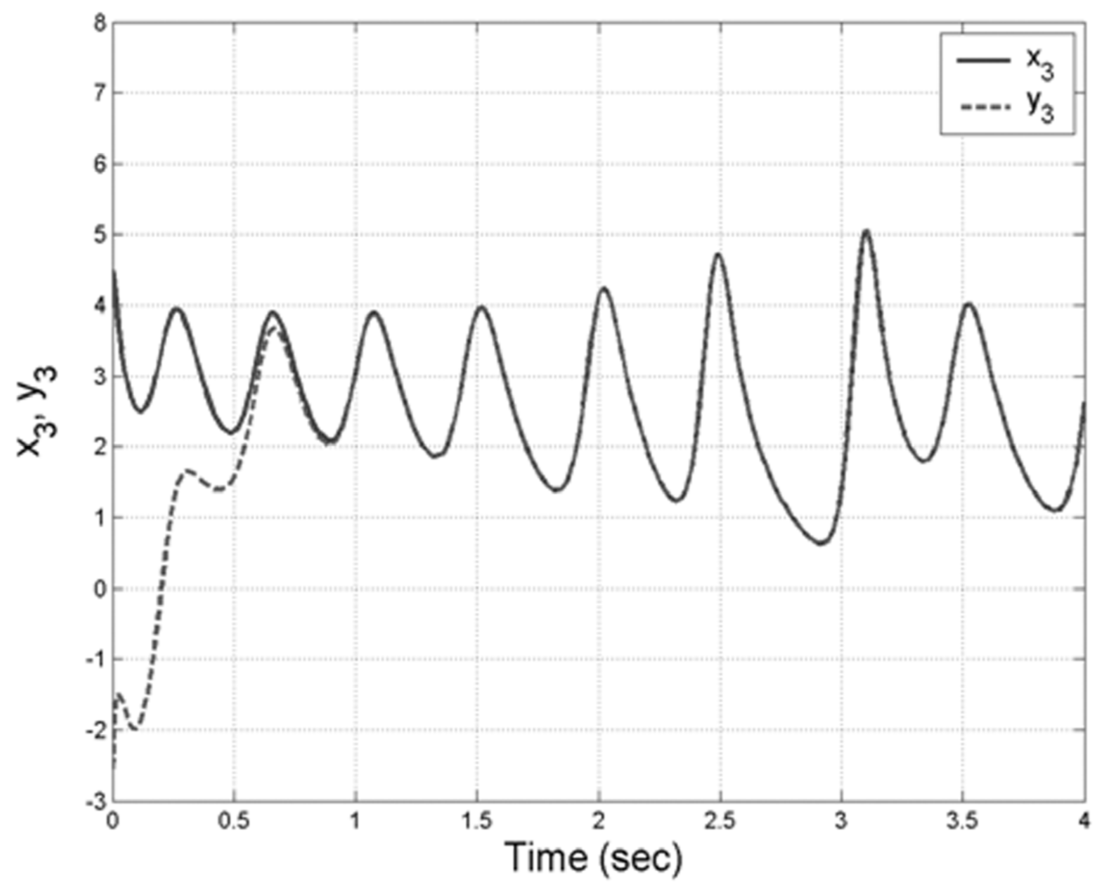

Figure 7: Hybrid synchronization of the states x_3 and y_3

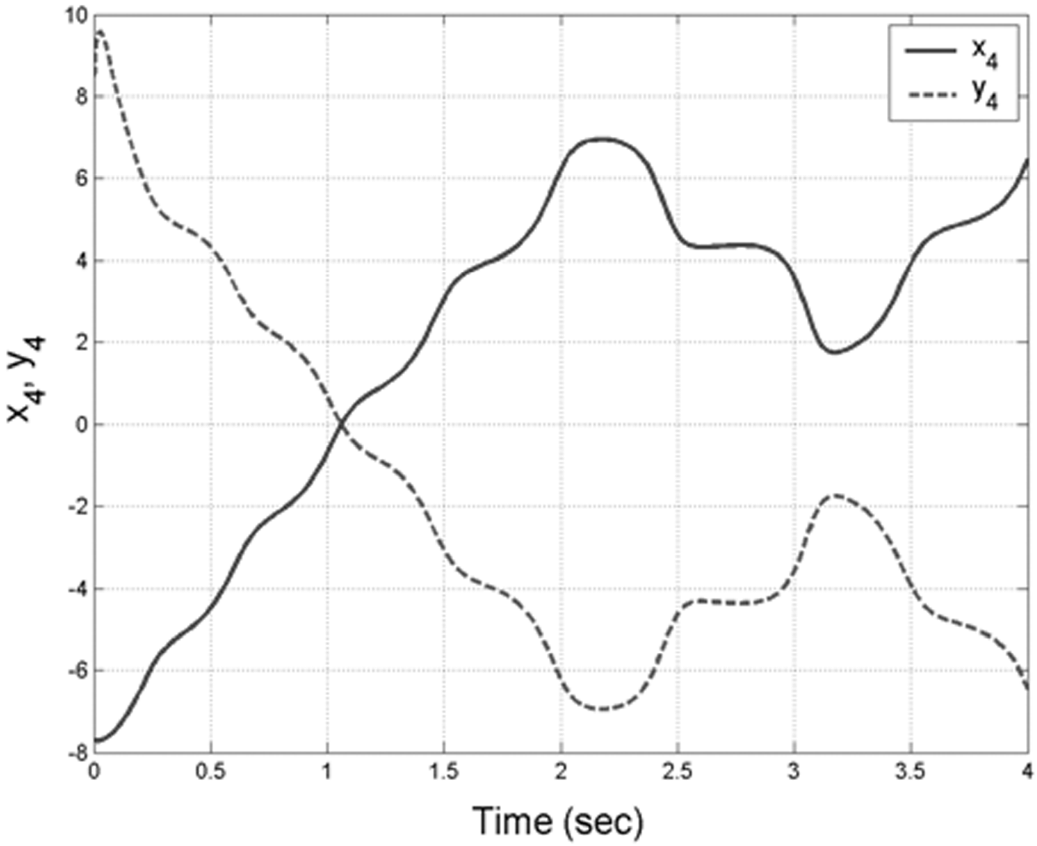

Figure 8: Hybrid synchronization of the states x_4 and y_4

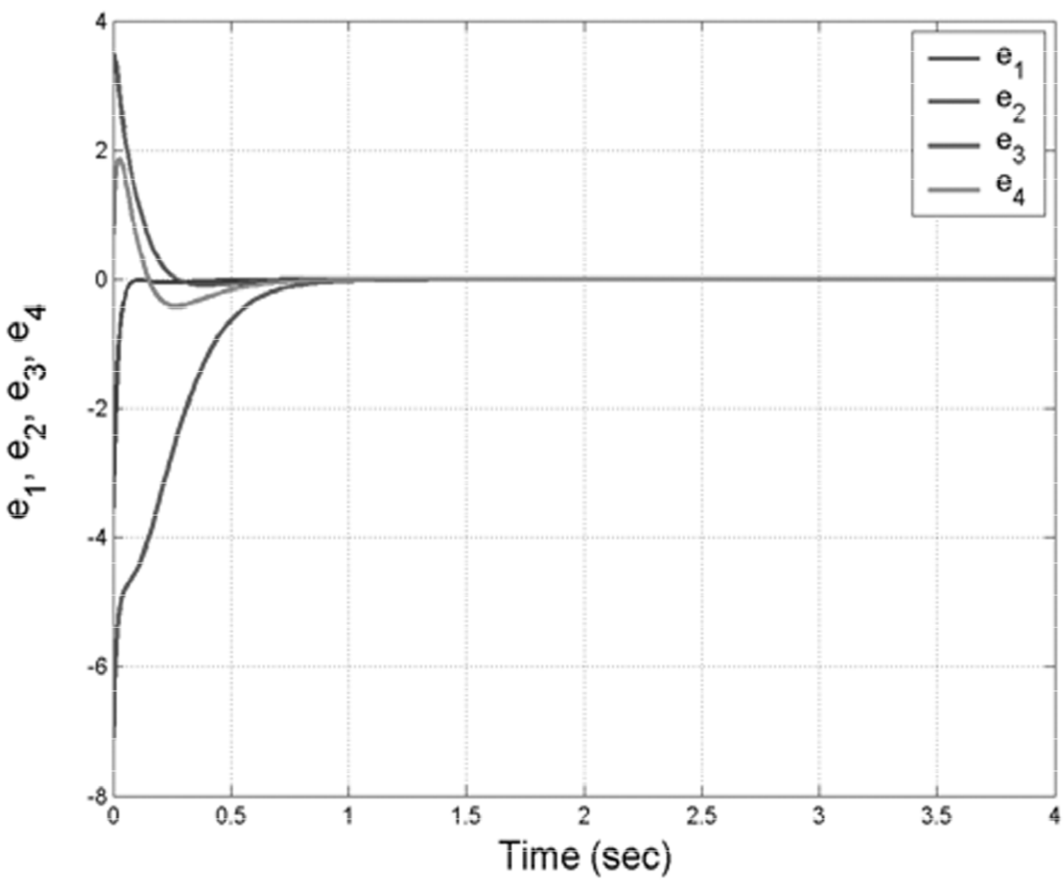

Figure 9: Time history of the hybrid synchronization errors

6. CONCLUSIONS

In this paper, a novel sliding mode controller has been designed for the hybrid synchronization of identical hyperchaotic systems. Lyapunov stability theory has been used to prove this main result of the work. Next, as an application of the main result, a sliding controller has been designed for achieving hyperchaos hybrid synchronization of identical hyperchaotic Vaidyanathan-Volos systems (2016). Numerical simulations using MATLAB have been provided to illustrate phase portraits of the hyperchaotic Vaidyanathan-Volos system and the novel sliding mode controller for the hyperchaos hybrid synchronization of identical hyperchaotic Vaidyanathan-Volos systems.

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