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A Novel Hyperchaotic System with Two Quadratic Nonlinearities, its Analysis and Synchronization via Integral Sliding Mode Control

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Abstract: First, this paper announces a nine-term novel 4-D hyperchaotic system with two quadratic nonlinearities. The phase portraits of the novel hyperchaotic system are displayed and the qualitative properties of the novel hyperchaotic system are discussed. We show that the novel hyperchaotic system has a unique equilibrium point at the origin, which is a saddle-point. The Lyapunov exponents of the novel 4-D hyperchaotic system are obtained as $L_1 = 1.02547$, $L_2 = 0.22242$, $L_3 = 0$ and $L_4 = -12.24995$. The maximal Lyapunov exponent (MLE) for the novel hyperchaotic system is obtained as$L_1 = 1.02547$. Also, the Kaplan-Yorke dimension of the novel hyperchaotic system is derived as $D_{KY} = 3.1019$. Hyperchaotic systems have important applications in secure communication and cryptosystems. Next, we derive new results for the global hyperchaos synchronization of the identical novel 4-D hyperchaotic systems via integral sliding mode control (ISMC). The global synchronization results for the novel hyperchaotic systems have been established using Lyapunov stability theory. In contrast with conventional sliding mode control (SMC), the system motion under integral sliding mode has a dimension equal to that of the state space. In ISMC, the system trajectory always starts from the sliding surface. Accordingly, the reaching phase is eliminated and robustness in the whole state space is promised. Numerical simulations with MATLAB have been shown to validate and demonstrate all the new results derived in this paper for the novel hyperchaotic system using integral sliding mode control.

Keywords: Chaos, chaotic systems, hyperchaos, hyperchaotic systems, hyperchaos synchronization, sliding manifold, integral sliding mode control, stability.

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], etc. A 5-D hyperchaotic system with three positive Lyapunov exponents was also recently found [42].

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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.

Chaos synchronization problem can be stated as follows. 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 the synchronization is to use the output of the master system to control the slave system so that the output of the slave system tracks the output of the master system asymptotically.

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, we derive a nine-term novel 4-D hyperchaotic system with two quadratic nonlinearities. We show that the novel hyperchaotic system has a unique equilibrium point at the origin, which is a saddle-point. The Lyapunov exponents of the novel hyperchaotic system are obtained as $L_1 = 1.02547$, $L_2 = 0.22242$, $L_3 = 0$ and $L_4 = -12.24995$. Also, the Kaplan-Yorke dimension of the novel hyperchaotic system is derived as $D_{KY} = 3.1019$.

The global hyperchaos synchronization results for the novel hyperchaotic systems have been established via integral sliding mode control (ISMC) method. In contrast with the conventional sliding mode control (SMC), the system motion under integral sliding mode has a dimension equal to that of the state space. In ISMC, the system trajectory always starts from the sliding surface. Accordingly, the reaching phase is eliminated and robustness in the whole state space is promised. Numerical simulations with MATLAB have been shown to illustrate the phase portraits of the novel hyperchaotic system and the synchronization results for the novel hyperchaotic system using integral sliding mode control.

2. A NOVEL 4-D HYPERCHAOTIC SYSTEM

In this section, we propose a novel autonomous hyperchaotic system described by

$$\begin{cases} \dot{x}_1 = a(x_2 - x_1) + x_4 \\ \dot{x}_2 = bx_1 - x_1 x_3 + x_4 \\ \dot{x}_3 = x_1 x_2 - x_3 \\ \dot{x}_4 = -cx_2 \end{cases} \tag{1}$$

where x_1, x_2, x_3, x_4 are the states and a, b, c are constant, positive parameters of the system.

The system (1) is a nine-term polynomial, autonomous, nonlinear system with only two quadratic nonlinearities.

The system (1) describes a *strange hyperchaotic attractor* for the parameter values

$$a = 10, \; b = 60, \; c = 2 \tag{2}$$

For numerical simulations, we take the initial values of the system (1) as

$$x_1(0) = 0.2, \;\; x_2(0) = 0.2, \;\; x_3(0) = 0.2, \;\; x_4(0) = 0.2 \tag{3}$$

The Lyapunov exponents of the novel system (1) are numerically obtained as

$$L_1 = 1.02547, \;\; L_2 = 0.22242, \;\; L_3 = 0, \;\; L_4 = -12.24995 \tag{4}$$

The presence of two positive Lyapunov exponents in the LE spectrum (4) of the novel system (1) shows that the system (1) is hyperchaotic.

Also, the maximum Lyapunov exponent (MLE) of the novel hyperchaotic system (1) is obtained as L_1 = 1.02547. Since the sum of the Lyapunov exponents in (4) is negative, the novel hyperchaotic system (1) is dissipative.

Figures 1-4 show the 3-D view of the strange hyperchaotic attractor of the novel hyperchaotic system (1) 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), respectively.

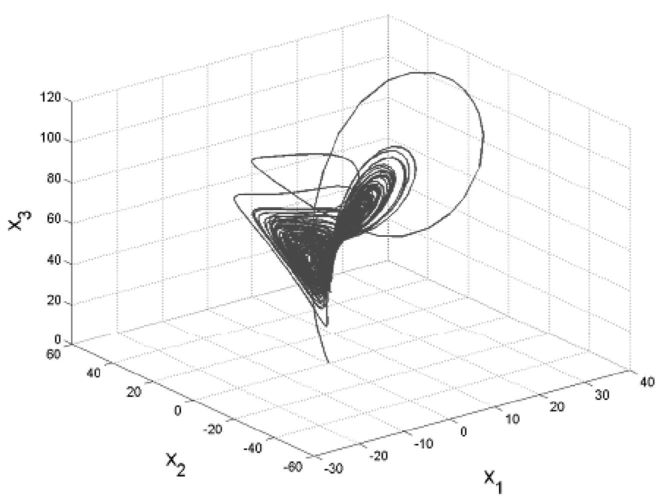

Figure 1. 3-D view of the novel hyperchaotic system in (x_1, x_2, x_3)–space

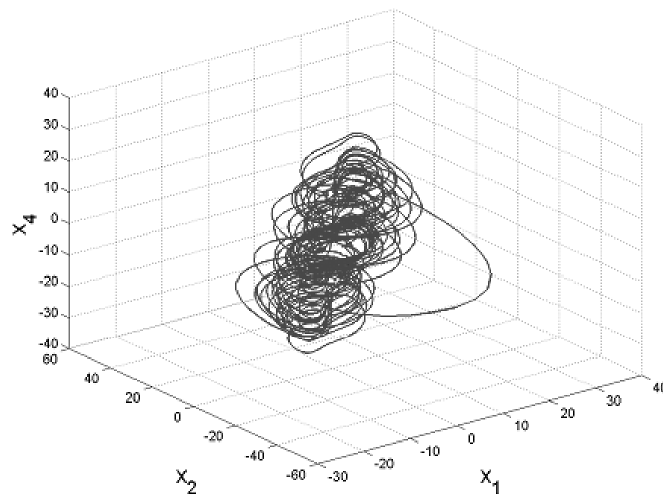

Figure 2. 3-D view of the novel hyperchaotic system in (x_1, x_2, x_4)–space

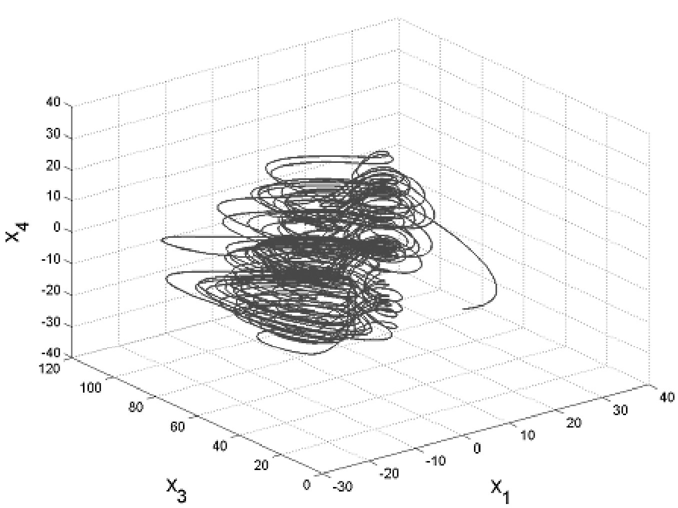

Figure 3. 3-D view of the novel hyperchaotic system in (x_1, x_3, x_4)–space

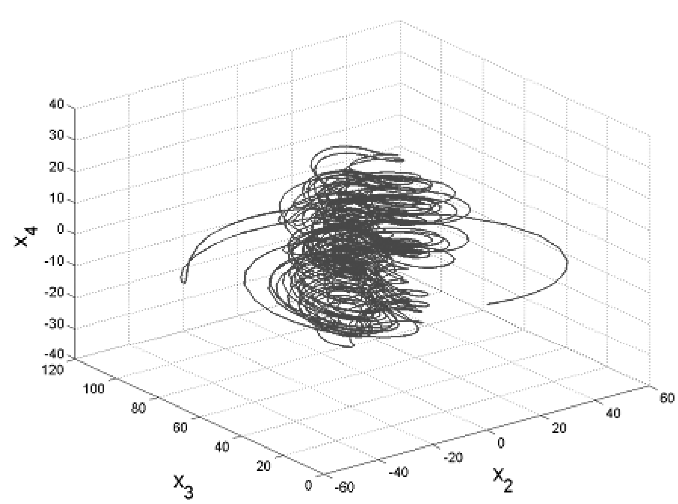

Figure 4. 3-D view of the novel hyperchaotic system in (x_2, x_3, x_4)–space

3. PROPERTIES OF THE NOVEL 4-D HYPERCHAOTIC SYSTEM

In this section, we detail the qualitative properties of the novel hyperchaotic system (1), which is described in Section 2.

3.1. Dissipativity

We write the system (1) in vector notation as

$$\dot{x} = f(x) = \begin{bmatrix} f_1(x_1, x_2, x_3, x_4) \\ f_2(x_1, x_2, x_3, x_4) \\ f_3(x_1, x_2, x_3, x_4) \\ f_4(x_1, x_2, x_3, x_4) \end{bmatrix}, \tag{5}$$

where

$$\begin{cases} f_1(x_1, x_2, x_3, x_4) = a(x_2 - x_1) + x_4 \\ f_2(x_1, x_2, x_3, x_4) = bx_1 - x_1 x_3 + x_4 \\ f_3(x_1, x_2, x_3, x_4) = x_1 x_2 - x_3 \\ f_4(x_1, x_2, x_3, x_4) = -cx_2 \end{cases} \tag{6}$$

We take the parameter values as

$$a = 10, \quad b = 60, \quad c = 2 \tag{7}$$

The divergence of the vector field f on R^4 is obtained as

$$\text{div} f = \frac{\partial f_1}{\partial x_1} + \frac{\partial f_2}{\partial x_2} + \frac{\partial f_3}{\partial x_3} + \frac{\partial f_4}{\partial x_4} = -a - 1 = -\mu, \tag{8}$$

where

$$\mu = a + 1 = 11 > 0 \tag{9}$$

Let Ω be any region in R^4 having a smooth boundary.

Let $\Omega(t) = \Phi_t(\Omega)$, where Φ_t is the flow of f.

Let $V(t)$ denote the hypervolume of $\Omega(t)$.

By Liouville's theorem, it follows that

$$\frac{dV}{dt} = \int_{\Omega(t)} (\text{div} f)\, dx_1\, dx_2\, dx_3\, dx_4 = \int_{\Omega(t)} (-\mu)\, dx_1\, dx_2\, dx_3\, dx_4 = -\mu V \tag{10}$$

Integrating the linear differential equation (10), we get the solution as

$$V(t) = V(0)\exp(-\mu t) \tag{11}$$

From Eq. (10), it follows that the hypervolume $V(t)$ shrinks to zero exponentially as $t \to \infty$.

Thus, the novel hyperchaotic system (1) is dissipative.

Hence, the asymptotic motion of the system (1) settles exponentially onto a set of measure zero, *i.e.* a strange attractor.

3.2. Symmetry

The novel hyperchaotic system (1) is invariant under the coordinates transformation

$$(x_1, x_2, x_3) \mapsto (-x_1, -x_2, x_3) \tag{12}$$

Since the transformation (12) persists for all values of the system parameters, the novel 4-D hyperchaotic system (1) has rotation symmetry about the x_3–axis and that any non-trivial trajectory must have a twin trajectory.

3.3. Invariance

The x_3–axis ($x_1 = 0$, $x_2 = 0$, $x_4 = 0$) is invariant for the system (1). Hence, all orbits of the system (1) starting on the x_3–axis stay in the x_3–axis for all values of time.

Also, this invariant motion is governed by the scalar differential equation

$$\dot{x}_3 = -x_3 \tag{13}$$

which is globally exponentially stable.

3.4. Equilibrium Points

The equilibrium points of the novel 3-D chaotic system (1) are obtained by solving the following nonlinear system of equations

$$\begin{cases} f_1(x_1, x_2, x_3, x_4) = a(x_2 - x_1) + x_4 = 0 \\ f_2(x_1, x_2, x_3, x_4) = bx_1 - x_1 x_3 + x_4 = 0 \\ f_3(x_1, x_2, x_3, x_4) = x_1 x_2 - x_3 = 0 \\ f_4(x_1, x_2, x_3, x_4) = -cx_2 = 0 \end{cases} \tag{14}$$

We take the parameter values as in the hyperchaotic case, *viz.*

$$a = 10, \quad b = 60, \quad c = 2 \tag{15}$$

Solving the equations (14) using the values (15), we obtain the unique equilibrium solution

$$E_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{16}$$

The Jacobian matrix of the novel chaotic system (1) at E_0 is obtained as

$$J_0 = J(E_0) = \begin{bmatrix} -10 & 10 & 0 & 1 \\ 60 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & -2 & 0 & 0 \end{bmatrix} \tag{18}$$

The eigenvalues of J_0 are numerically obtained as

$$\lambda_1 = -1, \quad \lambda_2 = -30.0531, \quad \lambda_3 = 0.2351, \quad \lambda_4 = 19.8181 \tag{19}$$

This shows that the equilibrium E_0 is a saddle point, which is unstable.

3.5. Lyapunov Exponents and Kaplan-Yorke Dimension

We take the parameter values of the novel 4-D system (1) as

$$a = 10, \quad b = 60, \quad c = 2 \tag{20}$$

We take the initial conditions of the novel system (1) as

$$x_1(0) = 0.2, \quad x_2(0) = 0.2, \quad x_3(0) = 0.2, \quad x_4(0) = 0.2 \tag{21}$$

The Lyapunov exponents of the system (1) are numerically obtained with MATLAB as

$$L_1 = 1.02547, \quad L_2 = 0.22242, \quad L_3 = 0, \quad L_4 = -12.24995 \tag{22}$$

Since there are two positive Lyapunov exponents in the LE spectrum (22), it follows that the novel system (1) is hyperchaotic. Since the sum of the Lyapunov exponents in (22) is negative, the novel system (1) is dissipative.

The Kaplan-Yorke dimension of the hyperchaotic system (1) is determined as

$$D_{KY} = 3 + \frac{L_1 + L_2 + L_3}{|L_4|} = 3.1019 \tag{23}$$

which is fractional.

The MATLAB plot of the Lyapunov exponents of the novel hyperchaotic system (1) is depicted in Figure 5.

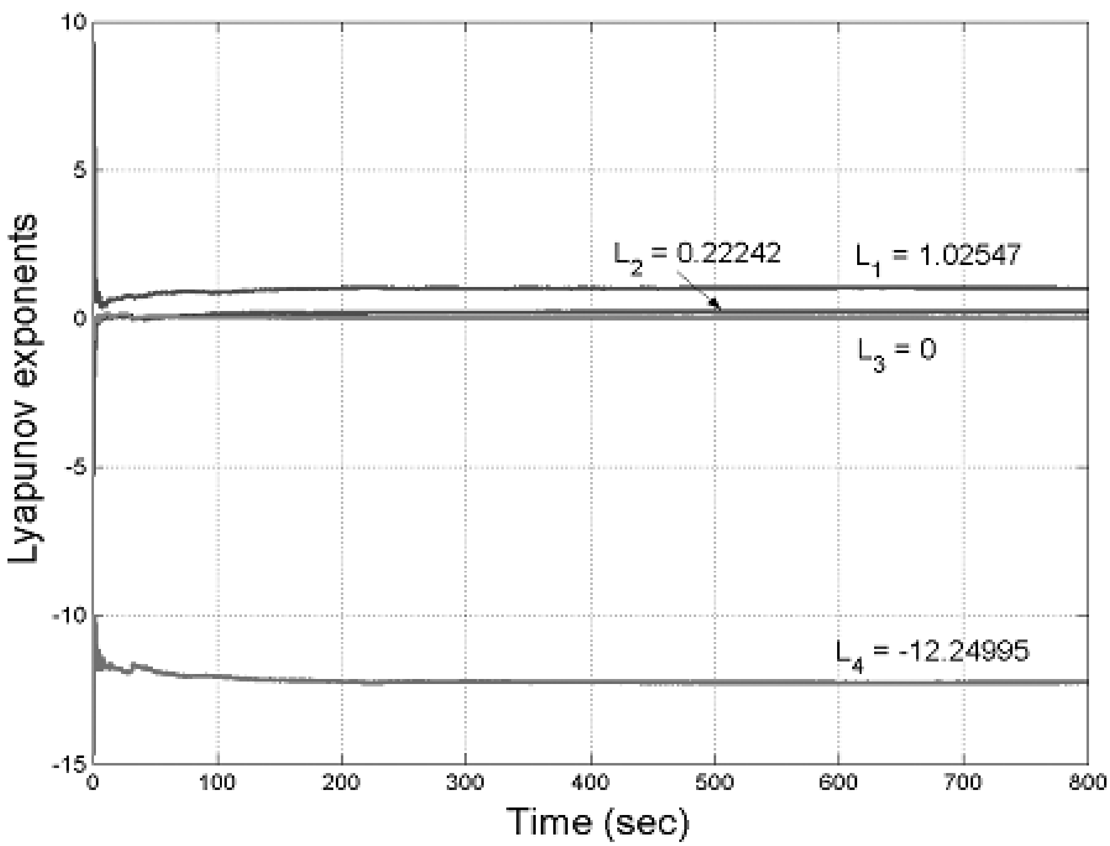

Figure 5: Lyapunov exponents of the novel hyperchaotic system

4. GLOBAL HYPERCHAOS SYNCHRONIZATION OF THE NOVEL IDENTICAL HYPERCHAOTIC SYSTEMS VIA INTEGRAL SLIDING MODE CONTROL

In this section, we derive new results for the global hyperchaos synchronization of the identical novel hyperchaotic systems with unknown parameters.

As the master system, we take the novel hyperchaotic system

$$\begin{cases} \dot{x}_1 = a(x_2 - x_1) + x_4 \\ \dot{x}_2 = bx_1 - x_1x_3 + x_4 \\ \dot{x}_3 = x_1x_2 - x_3 \\ \dot{x}_4 = -cx_2 \end{cases} \tag{24}$$

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

As the slave system, we take the controlled novel hyperchaotic system

$$\begin{cases} \dot{y}_1 = a(y_2 - y_1) + y_4 + u_1 \\ \dot{y}_2 = by_1 - y_1y_3 + y_4 + u_2 \\ \dot{y}_3 = y_1y_2 - y_3 + u_3 \\ \dot{y}_4 = -cy_2 + u_4 \end{cases} \tag{25}$$

where y_1, y_2, y_3, y_4 are state variables and u_1, u_2, u_3, u_4 are nonlinear controllers to be designed.

The synchronization error is defined by

$$\begin{cases} e_1 = y_1 - x_1 \\ e_2 = y_2 - x_2 \\ e_3 = y_3 - x_3 \\ e_4 = y_4 - x_4 \end{cases} \tag{26}$$

The error dynamics is easily obtained as

$$\begin{cases} \dot{e}_1 = a(e_2 - e_1) + e_4 + u_1 \\ \dot{e}_2 = be_1 + e_4 - y_1y_3 + x_1x_3 + u_2 \\ \dot{e}_3 = -e_3 + y_1y_2 - x_1x_2 + u_3 \\ \dot{e}_4 = -ce_2 + u_4 \end{cases} \tag{27}$$

Based on the sliding mode control theory [174], the integral sliding surface of each error variable e_i, (i = 1, 2, 3, 4) is defined as follows:

$$s_i = \left[\frac{d}{dt} + \lambda_i\right]\left[\int_0^t e_i(\tau)d\tau\right] = e_i + \lambda_i \int_0^t e_i(\tau)d\tau, \ (i = 1,2,3,4) \tag{28}$$

The derivative of each equation in (28) yields

$$\dot{s}_i = \dot{e}_i + \lambda_i e_i, \quad (i = 1,2,3,4) \tag{29}$$

The Hurwitz condition is satisfied if $\lambda_i > 0$ for i = 1, 2, 3, 4.

Based on the exponential reaching law [174], we set

$$\dot{s}_i = -\eta_i \operatorname{sgn}(s_i) - k_i s_i, \quad (i = 1, 2, 3, 4) \tag{30}$$

where sgn(·) is the sign function and η_i, κ_i, (i = 1, 2, 3, 4) are positive constants.

Comparing the equations (47) and (48), we get

$$\begin{cases} \dot{e}_1 + \lambda_1 e_1 = -\eta_1 \operatorname{sgn}(s_1) - k_1 s_1 \\ \dot{e}_2 + \lambda_2 e_2 = -\eta_2 \operatorname{sgn}(s_2) - k_2 s_2 \\ \dot{e}_3 + \lambda_3 e_3 = -\eta_3 \operatorname{sgn}(s_3) - k_3 s_3 \\ \dot{e}_4 + \lambda_4 e_4 = -\eta_4 \operatorname{sgn}(s_4) - k_4 s_4 \end{cases} \tag{31}$$

Using (27), we can rewrite the equations (31) as follows. S_1, S_2, S_3

$$\begin{cases} a(e_2 - e_1) + e_4 + u_1 + \lambda_1 e_1 = -\eta_1 \operatorname{sgn}(s_1) - k_1 s_1 \\ be_1 + e_4 - y_1 y_3 + x_1 x_3 + u_2 + \lambda_2 e_2 = -\eta_2 \operatorname{sgn}(s_2) - k_2 s_2 \\ -e_3 + y_1 y_2 - x_1 x_2 + u_3 + \lambda_3 e_3 = -\eta_3 \operatorname{sgn}(s_3) - k_3 s_3 \\ -ce_2 + u_4 + \lambda_4 e_4 = -\eta_4 \operatorname{sgn}(s_4) - k_4 s_4 \end{cases} \tag{32}$$

From (32), the control laws are obtained as follows.

$$\begin{cases} u_1 = -a(e_2 - e_1) - e_4 - \lambda_1 e_1 - \eta_1 \operatorname{sgn}(s_1) - k_1 s_1 \\ u_2 = -be_1 - e_4 + y_1 y_3 - x_1 x_3 - \lambda_2 e_2 - \eta_2 \operatorname{sgn}(s_2) - k_2 s_2 \\ u_3 = e_3 - y_1 y_2 + x_1 x_2 - \lambda_3 e_3 - \eta_3 \operatorname{sgn}(s_3) - k_3 s_3 \\ u_4 = ce_2 - \lambda_4 e_4 - \eta_4 \operatorname{sgn}(s_4) - k_4 s_4 \end{cases} \tag{33}$$

Next, we state and prove the main result of this section.

Theorem 1. The novel hyperchaotic systems (24) and (25) with constant system parameters are globally and asymptotically synchronized for all initial conditions $x(0)$, $y(0) \in R^4$ by the integral sliding mode control law (33), where the constants λ_i, η_i, κ_i are positive for i = 1, 2, 3, 4.

Proof. The result is proved using Lyapunov stability theory [175].

We consider the following quadratic Lyapunov function

$$V(s_1, s_2, s_3, s_4) = \frac{1}{2}\left(s_1^2 + s_2^2 + s_3^2 + s_4^2\right), \tag{34}$$

where S_1, S_2, $S_3 S_4$ are as defined in Eq. (28).

The time-derivative of is obtained as

$$\dot{V} = s_1 \dot{s}_1 + s_2 \dot{s}_2 + s_3 \dot{s}_3 + s_4 \dot{s}_4 \tag{35}$$

Substituting from Eq. (48) into (53), we obtain

$$\dot{V} = \sum_{i=1}^{4} s_i \left[-\eta_i \operatorname{sgn}(s_i) - k_i s_i \right] \tag{36}$$

Simplifying Eq. (36), we obtain

$$\dot{V} = -\eta_1 |s_1| - k_1 s_1^2 - \eta_2 |s_2| - k_2 s_2^2 - \eta_3 |s_3| - k_3 s_3^2 - \eta_4 |s_4| - k_4 s_4^2 \quad (37)$$

Since $\eta_i > 0$ and $k_i > 0$ for $i = 1, 2, 3, 4$ it is immediate that $e_i \to 0$ ($i = 1, 2, 3, 4$) as $t \to \infty$ for all initial conditions $e(0) \in R^4$.

This completes the proof. ■

4.1. Numerical Results

We use classical fourth-order Runge-Kutta method in MATLAB with step-size $h = 10^{-8}$ for solving the system of differential equations (24) and (25) when the integral sliding mode controller (33) is implemented.

For the novel hyperchaotic systems (24) and (25), the parameter values are taken as in the hyperchaotic case (2), i.e.

$$a = 10, \ b = 60, \ c = 2 \quad (38)$$

We take the sliding constants as

$$\eta_i = \lambda_i = 0.1, \ \ k_i = 20, \ \ (i = 1, 2, 3, 4) \quad (39)$$

The initial values of the hyperchaotic system (24) are taken as

$$x_1(0) = 6.1, \ x_2(0) = 3.9, \ x_3(0) = 8.5, \ x_4(0) = 14.1 \quad (40)$$

The initial values of the hyperchaotic system (25) are taken as

$$y_1(0) = 9.2, \ y_2(0) = 4.6, \ y_3(0) = 17.2, \ y_4(0) = 5.8 \quad (41)$$

Figures 6-9 depict the complete synchronization of the hyperchaotic systems (24) and (25).

Figure 10 depicts the time-history of the synchronization errors e_1, e_2, e_3, e_4.

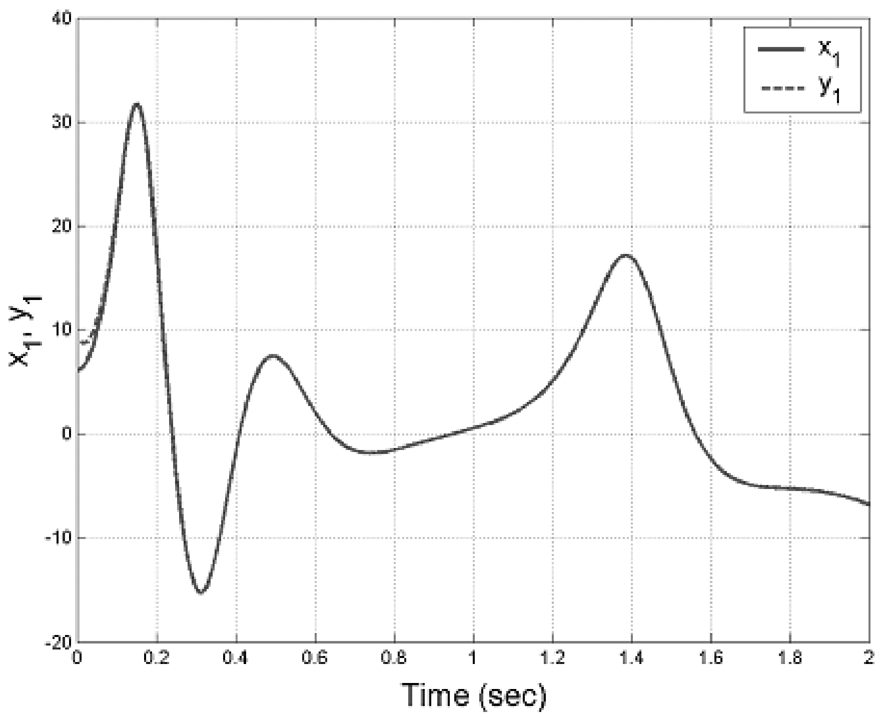

Figure 6: Complete synchronization of the states x_1 and y_1

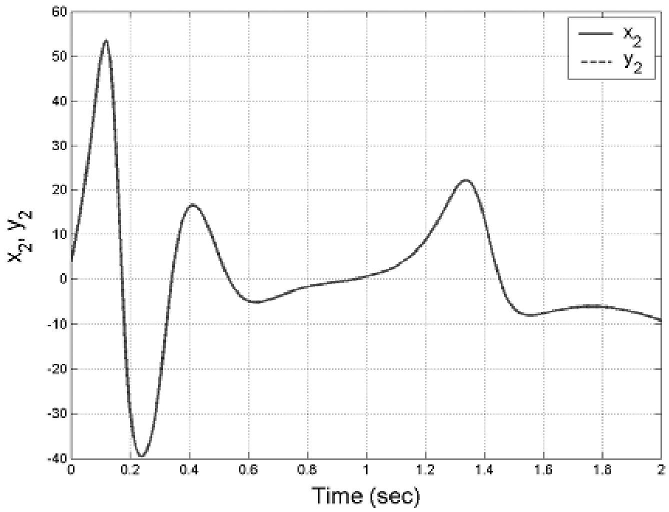

Figure 7: Complete synchronization of the states x_2 and y_2

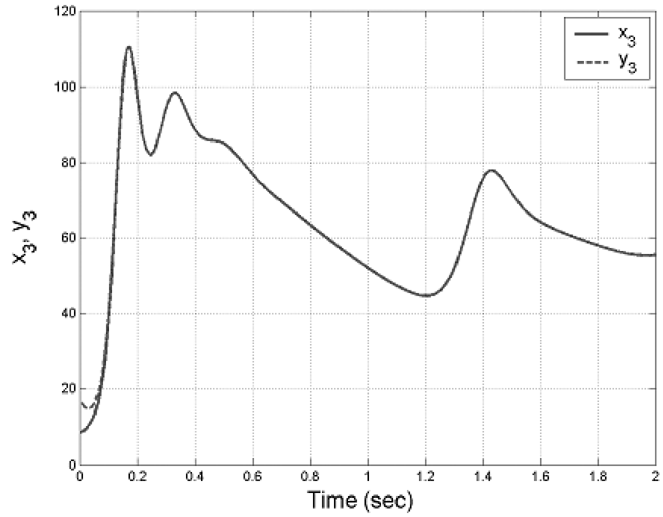

Figure 8: Complete synchronization of the states x_3 and y_3

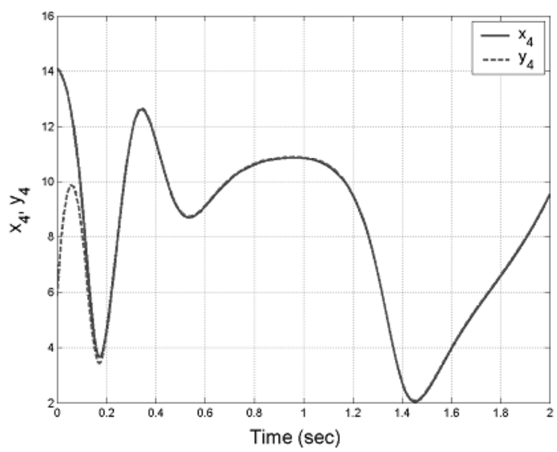

Figure 9: Complete synchronization of the states x_4 and y_4

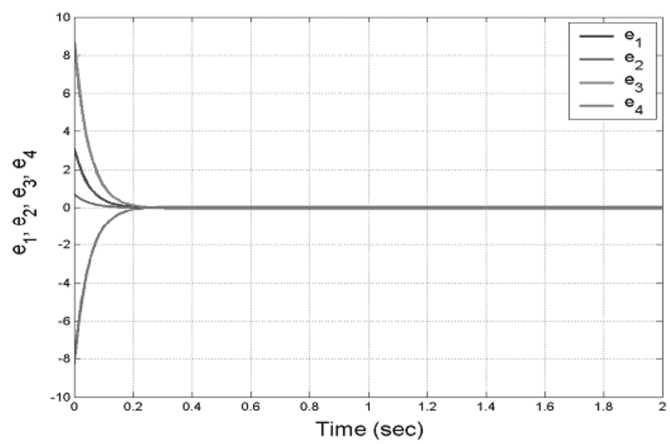

Figure 10: Time history of the chaos synchronization errors e_1, e_2, e_3, e_4

6. CONCLUSIONS

In this paper, we described a nine-term novel 4-D hyperchaotic system with two quadratic nonlinearities. The phase portraits of the novel hyperchaotic system were displayed and the qualitative properties of the novel hyperchaotic system were discussed. The Lyapunov exponents of the novel 4-D hyperchaotic system have been obtained as $L_1 = 1.02547$, $L_2 = 0.22242$, $L_3 = 0$ and $L_4 = -12.24995$. The maximal Lyapunov exponent (MLE) for the novel hyperchaotic system is deduced as $L_1 = 1.02547$. Also, the Kaplan-Yorke dimension of the novel hyperchaotic system has beenderived as $D_{KY} = 3.1019$. Hyperchaotic systems have important applications in secure communication and cryptosystems. Next, we derived new results for the global hyperchaos synchronization of the identical novel 4-D hyperchaotic systems via integral sliding mode control (ISMC). The global synchronization results for the novel hyperchaotic systems have been established using Lyapunov stability theory. In contrast with conventional sliding mode control (SMC), the system motion under integral sliding mode has a dimension equal to that of the state space. In ISMC, the system trajectory always starts from the sliding surface. Accordingly, the reaching phase is eliminated and robustness in the whole state space is promised. Numerical simulations with MATLAB have been shown to validate and demonstrate all the new results derived in this paper for the novel hyperchaotic system using integral sliding mode control.

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