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Sliding Controller Design for the Global Chaos Synchronization of Enzymes-Substrates Systems

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Abstract: In the recent decades, there is significant interest in the literature in the application of chaos in physical, electrical, chemical and biological systems. This paper investigates research in the dynamic analysis and global chaos synchronization of enzymes-substrate reactions system with ferroelectric behaviour in brain waves which was studied by Enjieu Kadji, Chabi Orou, Yamapi and Woafo (2007). The enzymes-substrates system is a 2-D non-autonomous system with a cosinusoidal forcing term. This paper depicts the phase portraits of the 2-D enzymes-substrates system when the system undergoes chaotic behaviour. Next, this paper derives new results for the sliding mode controller (SMC) design for globally synchronizing the identical enzyme-substrates biological systems. The main control result derived in this work is proved using Lyapunov stability theory. MATLAB plots have been shown in this paper to illustrate the main results for the enzyme-substrates system.

Keywords: Chaos, enzymes-substrate reactions, biology, synchronization, sliding mode control, etc.

1. Introduction

Chaos theory is a modern research field which discusses the qualitative and numerical study of unstable aperiodic behaviour in deterministic nonlinear dynamical systems. A dynamical system is called chaotic if it satisfies the three properties: boundedness, infinite recurrence and sensitive dependence on initial conditions [1-2].

The first famous chaotic system was discovered by Lorenz, when he was developing a 3-D weather model for atmospheric convection in 1963 [3], and subsequently, Rössler discovered a 3-D chaotic system in 1976 [4], which was constructed during the study of a chemical reaction.

Recently, many 3-D chaotic systems have been announced in the literature such as Arneodo system [5], Sprott systems [6], Chen system [7], Lü-Chen system [8], Cai system [9], Tigan system [10], etc. Many new chaotic systems have been also discovered in the recent years like Sundarapandian systems [11, 12], Vaidyanathan systems [13-43], Pehlivan system [44], Pham system [45], etc.

In control theory, active control method is used when the parameters are available for measurement [46-65]. Adaptive control is a popular control technique used for stabilizing systems when the system parameters are unknown [66-79]. There are also other popular methods available for control and synchronization of systems such as backstepping control method [80-86], sliding mode control method [87-98], etc.

Recently, chaos theory is found to have important applications in several areas such as chemistry [99-107], biology [108-125], memristors [126-128], electrical circuits [129], etc.

Coherent oscillations in biological systems are studied by Frohlich [130] and the following suggestions were made which are taken as a physical basis for theoretical investigation of enzymatic substrate reaction with ferroelectric behaviour in brain waves model [131].

1. When metabolic energy is available, long-wavelength electric vibrations are very strongly and coherently excited in active biological system.
2. Biological systems have metastable states with a very high electric polarization.

These long range interactions may lead to a selective transport of enzymes, and hence specific chemical reactions may become possible. Enjieu Kadji, Chabi Orou, Yamapi and Woafo (2007) derived enzymes-substrates reactions system with ferroelectric behaviour in brain waves [132]. Specifically, chaotic behaviour was noted for the 2-D enzyme-substrate reactions system. This paper discusses the chaotic properties of the enzyme-substrates reactions system, and MATLAB plots are shown for the phase portraits of the chaotic system.

This paper also derives new results of adaptive backstepping controller design for the global chaos synchronization of enzymes-substrate systems, which are established using Vaidyanathan's novel sliding control method [97] for global chaos synchronization of chaotic systems. MATLAB plots are shown to illustrate all the main results derived in this work.

2. Enzymes-Substrates Reaction System

Enjieu Kadji, Chabi Orou, Yamapi and Woafo derived enzyme-substrate reactions system with ferroelectric behaviour in brain waves [132], which is given by the differential equation

$$\ddot{x} - \mu\left(1 - x^2 + ax^4 - bx^6\right)\dot{x} + x \quad E\cos(\Omega t) \tag{1}$$

In (1), a, b are positive parameters, μ is the parameter of nonlinearity, while E and Ω are the amplitude and the frequency of the external cosinusoidal excitation, respectively.

The enzymes-substrates reaction system (1) can be compactly put in system form as

$$\begin{cases} \dot{x} = y \\ \dot{y} = \mu y\left(1 - x^2 + ax^4 - bx^6\right) - x + E\cos(\Omega t) \end{cases} \tag{2}$$

For the external excitation, we take the constants as

$$E = 8.27, \quad \Omega = 3.465 \tag{3}$$

The biological system (2) is chaotic when the system parameters are chosen as

$$a = 2.55, \quad b = 1.70, \quad \mu = 2.001 \tag{4}$$

For numerical simulations, we take the initial conditions $x(0) = 0.1$ and $y(0) = 0.1$.

The 2-D phase portrait of the enzymes-substrates biological reaction system is depicted in Fig. 1.

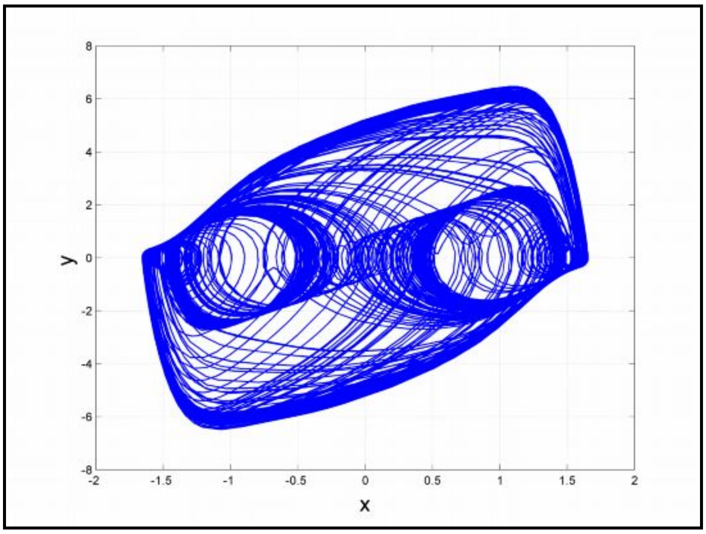

Figure 1. The 2-D phase portrait of the enzymes-substrates biological reaction system

3. Sliding Controller Design for the Global Chaos Synchronization of the Enzymes-Substrates Reaction Systems

In this section, we design a sliding mode controller (SMC) for globally synchronizing the enzymes-substrates reaction systems. It is supposed that the constants E and Ω associated with the external excitation $f(t) = E\cos(\Omega t)$ are maintained at the constant values given in equation (3). It is also supposed that the nonlinear parameter μ is maintained at the constant value given in equation (4).

As the master system, we consider the controlled enzymes-substrates reaction system given by

$$\begin{cases} \dot{x}_1 = y_1 \\ \dot{y}_1 = \mu y_1\left(1 - x_1^2 + a x_1^4 - b x_1^6\right) - x_1 + E\cos(\Omega t) \end{cases} \tag{5}$$

In (5), x_1, y_1 are the states and a, b, μ, E, Ω are constant, positive, parameters.

As the slave system, we consider the controlled enzymes-substrates reaction system given by

$$\begin{cases} \dot{x}_2 = y_2 \\ \dot{y}_2 = \mu y_2\left(1 - x_2^2 + a x_2^4 - b x_2^6\right) - x_2 + E\cos(\Omega t) + u \end{cases} \tag{6}$$

In (6), x_2, y_2 are the states and u is the sliding mode controller to be determined.

Now, we define the chaos synchronization errors as

$$\begin{cases} e_x = x_2 - x_1 \\ e_y = y_2 - y_1 \end{cases} \tag{7}$$

Then the error dynamics is obtained as

$$\begin{cases} \dot{e}_x = e_y \\ \dot{e}_y = -e_x + \mu e_y + \mu\left(x_2^2 y_2 - x_1^2 y_1\right) + a\mu\left(x_2^4 y_2 - x_1^4 y_1\right) - b\mu\left(x_2^6 y_2 - x_1^6 y_1\right) + u \end{cases} \tag{8}$$

Next, we arrange the error system (8) in matrix form as

$$\dot{e} = Ae + \Psi(X_1, X_2) + Bu \tag{9}$$

where

$$e = \begin{bmatrix} e_x \\ e_y \end{bmatrix}, \quad A = \begin{bmatrix} 0 & 1 \\ -1 & \mu \end{bmatrix}, \quad X_1 = \begin{bmatrix} x_1 \\ y_1 \end{bmatrix}, \quad X_2 = \begin{bmatrix} x_2 \\ y_2 \end{bmatrix}, \quad B \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{10}$$

and

$$\Psi\left(X_1, X_2\right) = \begin{bmatrix} 0 \\ \Phi(X_1, X_2) \end{bmatrix} \tag{11}$$

with

$$\Phi(X_1, X_2) = \mu\left(x_2^2 y_2 - x_1^2 y_1\right) + a\mu\left(x_2^4 y_2 - x_1^4 y_1\right) - b\mu\left(x_2^6 y_2 - x_1^6 y_1\right) \tag{12}$$

We define the nonlinear control u as

$$u = -\Phi(X_1, X_2) + v \tag{13}$$

Then the nonlinear error dynamics (9) reduces to the linear error dynamics

$$\dot{e} = Ae + Bv \tag{14}$$

where $v(t)$ is a sliding mode controller to be determined using Vaidyanathan's novel sliding control method [97].

First, we shall verify that (A, B) is completely controllable.

We take the parameter values as in the chaotic case, i.e.

$$a = 2.55, \quad b = 1.70, \quad \mu = 2.001 \tag{15}$$

The controllability matrix for the linear pair (A, B) is easily obtained as

$$Q = \begin{bmatrix} B & AB \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & \mu \end{bmatrix} \tag{16}$$

We find that $\det(Q) = -1 \neq 0$. Thus, the controllability matrix Q has full rank.

Hence, by Kalman's rank condition for controllability [133], the pair (A, B) is completely controllable.
We select the sliding variable as

$$s = Ce = \begin{bmatrix} 10 & 1 \end{bmatrix} e = 10e_x + e_y \tag{17}$$

With the choice of $C = \begin{bmatrix} 10 & 1 \end{bmatrix}$, the eigenvalues of the matrix $E = \left[I - B(CB)^{-1} C \right] A$ are given by

$$\text{eig}(E) = \{-10, 0\}. \tag{18}$$

This shows that the dynamics along the sliding manifold is globally asymptotically stable.
Next, we take the sliding constants as $k = 6$ and $q = 0.2$.
Then the sliding mode control v is obtained by the Vaidyanathan's theorem [97] as

$$v(t) = -(CB)^{-1} \left[C(kI + A)e + qs^2 \,\text{sgn}(s) \right] \tag{19}$$

A simple calculation gives

$$v(t) = -59e_x - 18.001e_y - 0.2s^2 \,\text{sgn}(s) \tag{20}$$

As an application of Vaidyanathan's theorem [97], we obtain the following result.

Theorem 1. The nonlinear enzymes-substrates reaction systems (5) and (6) are globally and asymptotically synchronized for all initial conditions by the sliding mode control u given by (13), where $\Phi(X_1, X_2)$ is defined by (12) and v is defined by (17). ■

4. Numerical Simulations

We use classical fourth-order Runge-Kutta method in MATLAB with step-size $h = 10^{-8}$ for solving the systems of differential equations given by (5) and (6), when the sliding mode control law (12) is applied.

We take the sliding constants as $k = 6$ and $q = 0.2$.
We take the initial conditions of the master system (5) as

$$x_1(0) = 2.5, \quad y_1(0) = 3.7 \tag{21}$$

We take the initial conditions of the slave system (6) as

$$x_2(0) = 0.8, \quad y_2(0) = 6.2 \tag{22}$$

The parameter values are taken as in (3) and (4) for the chaotic case, viz.

$$E = 8.27, \; \Omega = 3.465, \; a = 2.55, \; b = 1.70, \; \mu = 2.001 \tag{23}$$

Figures 2-3 show the global chaos synchronization of the enzymes-substrates reaction systems (5) and (6).

Figure 4 shows the time-history of the chaos synchronization errors $e_x(t), e_y(t)$.

From Figure 4, it is clear that the synchronization errors converge asymptotically as time gets large.

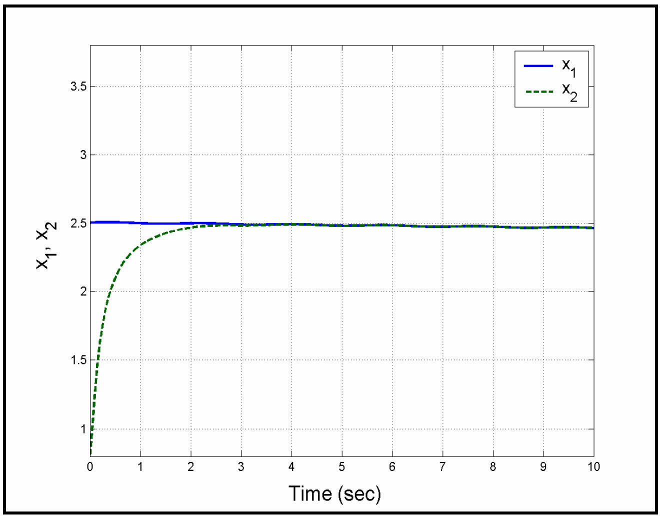

Figure 2. Synchronization of the states $x_1(t), x_2(t)$

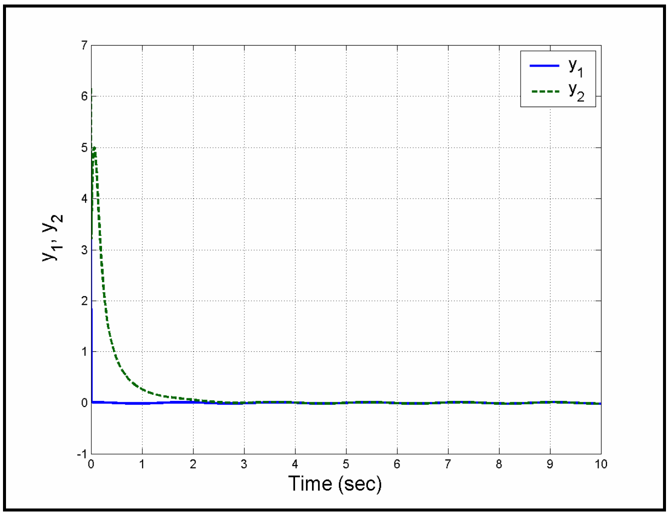

Figure 3. Synchronization of the states $y_1(t), y_2(t)$

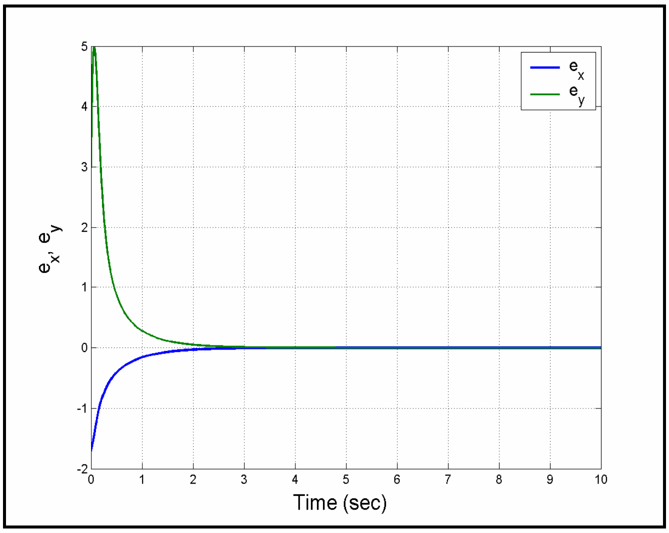

Figure 4. Time-history of the synchronization errors $e_x(t), e_y(t)$

5. Conclusions

In this paper, new results have been derived for the enzymes-substrates reaction with ferroelectric behaviour in brain waves discovered by Enjieu Kadji, Chabi Orou, Yamapi and Woafo (2007). This paper has presented a good description and dynamic analysis of the chaotic 2-D non-autonomous attractor describing the enzymes-substrates reaction systems. Then this paper presented new results for the sliding controller design for the global chaos synchronization of the identical enzymes-substrates reaction systems. Also, numerical simulations using MATLAB were shown to elucidate the main results.

References

1. Azar, A. T., and Vaidyanathan, S., Chaos Modeling and Control Systems Design, Studies in Computational Intelligence, Vol. 581, Springer, New York, USA, 2015.
2. Azar, A. T., and Vaidyanathan, S., Computational Intelligence Applications in Modeling and Control, Studies in Computational Intelligence, Vol. 575, Springer, New York, USA, 2015.
3. Lorenz, E. N., Deterministic nonperiodic flow, Journal of the Atmospheric Sciences, 1963, 20, 130-141.
4. Rössler, O. E., An equation for continuous chaos, Physics Letters A, 1976, 57, 397-398.
5. Arneodo, A., Coullet, P., and Tresser, C., Possible new strange attractors with spiral structure, Communications in Mathematical Physics, 1981, 79, 573-579.
6. Sprott, J. C., Some simple chaotic flows, Physical Review E, 1994, 50, 647-650.
7. Chen, G., and Ueta, T., Yet another chaotic attractor, International Journal of Bifurcation and Chaos, 1999, 9, 1465-1466.
8. Lü, J., and Chen, G., A new chaotic attractor coined, International Journal of Bifurcation and Chaos, 2002, 12, 659-661.
9. Cai, G., and Tan, Z., Chaos synchronization of a new chaotic system via nonlinear control, Journal of Uncertain Systems, 2007, 1, 235-240.
10. Tigan, G., and Opris, D., Analysis of a 3D chaotic system, Chaos, Solitons and Fractals, 2008, 36, 1315-1319.
11. Sundarapandian, V., and Pehlivan, I., Analysis, control, synchronization and circuit design of a novel chaotic system, Mathematical and Computer Modelling, 2012, 55, 1904-1915.
12. Sundarapandian, V., Analysis and anti-synchronization of a novel chaotic system via active and adaptive controllers, Journal of Engineering Science and Technology Review, 2013, 6, 45-52.
13. Vaidyanathan, S., A new six-term 3-D chaotic system with an exponential nonlinearity, Far East Journal of Mathematical Sciences, 2013, 79, 135-143.
14. Vaidyanathan, S., Analysis and adaptive synchronization of two novel chaotic systems with hyperbolic sinusoidal and cosinusoidal nonlinearity and unknown parameters, Journal of Engineering Science and Technology Review, 2013, 6, 53-65.
15. Vaidyanathan, S., A new eight-term 3-D polynomial chaotic system with three quadratic nonlinearities, Far East Journal of Mathematical Sciences, 2014, 84, 219-226.
16. Vaidyanathan, S., Analysis, control and synchronisation of a six-term novel chaotic system with three quadratic nonlinearities, International Journal of Modelling, Identification and Control, 2014, 22, 41-53.
17. Vaidyanathan, S., and Madhavan, K., Analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system, International Journal of Control Theory and Applications, 2013, 6, 121-137.
18. Vaidyanathan, S., Analysis and adaptive synchronization of eight-term 3-D polynomial chaotic systems with three quadratic nonlinearities, European Physical Journal: Special Topics, 2014, 223, 1519-1529.
19. Vaidyanathan, S., Volos, C., Pham, V. T., Madhavan, K., and Idowu, B. A., Adaptive backstepping control, synchronization and circuit simulation of a 3-D novel jerk chaotic system with two hyperbolic sinusoidal nonlinearities, Archives of Control Sciences, 2014, 24, 257-285.
20. Vaidyanathan, S., Generalised projective synchronisation of novel 3-D chaotic systems with an exponential non-linearity via active and adaptive control, International Journal of Modelling, Identification and Control, 2014, 22, 207-217.
21. Vaidyanathan, S., and Azar, A.T., Analysis and control of a 4-D novel hyperchaotic system, Studies in Computational Intelligence, 2015, 581, 3-17.
22. Vaidyanathan, S., Volos, C., Pham, V.T., and Madhavan, K., Analysis, adaptive control and synchronization of a novel 4-D hyperchaotic hyperjerk system and its SPICE implementation, Archives of Control Sciences, 2015, 25, 135-158.

23. Vaidyanathan, S., Volos, C., and Pham, V.T., Hyperchaos, adaptive control and synchronization of a novel 5-D hyperchaotic system with three positive Lyapunov exponents and its SPICE implementation, Archives of Control Sciences, 2014, 24, 409-446.
24. Vaidyanathan, S., A ten-term novel 4-D hyperchaotic system with three quadratic nonlinearities and its control, International Journal of Control Theory and Applications, 2013, 6, 97-109.
25. Vaidyanathan, S., Analysis, properties and control of an eight-term 3-D chaotic system with an exponential nonlinearity, International Journal of Modelling, Identification and Control, 2015, 23, 164-172.
26. Vaidyanathan, S., Azar, A.T., Rajagopal, K., and Alexander, P., Design and SPICE implementation of a 12-term novel hyperchaotic system and its synchronisation via active control, International Journal of Modelling, Identification and Control, 2015, 23, 267-277.
27. Vaidyanathan, S., Qualitative analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system with a quartic nonlinearity, International Journal of Control Theory and Applications, 2014, 7, 1-20.
28. Vaidyanathan, S., Qualitative analysis and control of an eleven-term novel 4-D hyperchaotic system with two quadratic nonlinearities, International Journal of Control Theory and Applications, 2014, 7, 35-47.
29. Vaidyanathan, S., and Pakiriswamy, S., A 3-D novel conservative chaotic system and its generalized projective synchronization via adaptive control, Journal of Engineering Science and Technology Review, 2015, 8, 52-60.
30. Vaidyanathan, S., Volos, C.K., and Pham, V.T., Analysis, adaptive control and adaptive synchronization of a nine-term novel 3-D chaotic system with four quadratic nonlinearities and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 181-191.
31. Vaidyanathan, S., Rajagopal, K., Volos, C.K., Kyprianidis, I.M., and Stouboulos, I.N., Analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system with three quadratic nonlinearities and its digital implementation in LabVIEW, Journal of Engineering Science and Technology Review, 2015, 8, 130-141.
32. Pham, V.T., Volos, C.K., Vaidyanathan, S., Le, T.P., and Vu, V.Y., A memristor-based hyperchaotic system with hidden attractors: Dynamics, synchronization and circuital emulating, Journal of Engineering Science and Technology Review, 2015, 8, 205-214.
33. Pham, V.T., Volos, C.K., and Vaidyanathan, S., Multi-scroll chaotic oscillator based on a first-order delay differential equation, Studies in Computational Intelligence, 2015, 581, 59-72.
34. Vaidyanathan, S., Volos, C.K., Kyprianidis, I.M., Stouboulos, I.N., and Pham, V.T., Analysis, adaptive control and anti-synchronization of a six-term novel jerk chaotic system with two exponential nonlinearities and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 24-36.
35. Vaidyanathan, S., Volos, C.K., and Pham, V.T., Analysis, control, synchronization and SPICE implementation of a novel 4-D hyperchaotic Rikitake dynamo system without equilibrium, Journal of Engineering Science and Technology Review, 2015, 8, 232-244.
36. Sampath, S., Vaidyanathan, S., Volos, C.K., and Pham, V.T., An eight-term novel four-scroll chaotic system with cubic nonlinearity and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 1-6.
37. Vaidyanathan, S., A 3-D novel highly chaotic system with four quadratic nonlinearities, its adaptive control and anti-synchronization with unknown parameters, Journal of Engineering Science and Technology Review, 2015, 8, 106-115.
38. Vaidyanathan, S., Pham, V.-T., and Volos, C. K., A 5-D hyperchaotic Rikitake dynamo system with hidden attractors, European Physical Journal: Special Topics, 2015, 224, 1575-1592.
39. Pham, V.-T., Vaidyanathan, S., Volos, C. K., and Jafari, S., Hidden attractors in a chaotic system with an exponential nonlinear term, European Physical Journal: Special Topics, 2015, 224, 1507-1517.
40. Vaidyanathan, S., Hyperchaos, qualitative analysis, control and synchronisation of a ten-term 4-D hyperchaotic system with an exponential nonlinearity and three quadratic nonlinearities, International Journal of Modelling, Identification and Control, 2015, 23, 380-392.
41. Vaidyanathan, S., and Azar, A. T., Analysis, control and synchronization of a nine-term 3-D novel chaotic system, Studies in Computational Intelligence, 2015, 581, 19-38.
42. Vaidyanathan, S., and Volos, C., Analysis and adaptive control of a novel 3-D conservative no-equilibrium chaotic system, Archives of Control Sciences, 2015, 25, 333-353.

43. Vaidyanathan, S., Analysis, control and synchronization of a 3-D novel jerk chaotic system with two quadratic nonlinearities, Kyungpook Mathematical Journal, 2015, 55, 563-586.
44. Pehlivan, I., Moroz, I. M., and Vaidyanathan, S., Analysis, synchronization and circuit design of a novel butterfly attractor, Journal of Sound and Vibration, 2014, 333, 5077-5096.
45. Pham, V. T., Volos, C., Jafari, S., Wang, X., and Vaidyanathan, S., Hidden hyperchaotic attractor in a novel simple memristic neural network, Optoelectronics and Advanced Materials – Rapid Communications, 2014, 8, 1157-1163.
46. Sundarapandian, V., Output regulation of Van der Pol oscillator, Journal of the Institution of Engineers (India): Electrical Engineering Division, 88, 20-24, 2007.
47. Sundarapandian, V., Output regulation of the Lorenz attractor, Far East Journal of Mathematical Sciences, 2010, 42, 289-299.
48. Vaidyanathan, S., and Rajagopal, K., Anti-synchronization of Li and T chaotic systems by active nonlinear control, Communications in Computer and Information Science, 2011, 198, 175-184.
49. Vaidyanathan, S., and Rasappan, S., Global chaos synchronization of hyperchaotic Bao and Xu systems by active nonlinear control, Communications in Computer and Information Science, 2011, 198, 10-17.
50. Vaidyanathan, S., Output regulation of the unified chaotic system, Communications in Computer and Information Science, 2011, 198, 1-9.
51. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of hyperchaotic Pang and Wang systems by active nonlinear control, 2011, 198, 84-93.
52. Vaidyanathan, S., Hybrid chaos synchronization of Liu and Lu systems by active nonlinear control, Communications in Computer and Information Science, 2011, 204, 1-10.
53. Sarasu, P., and Sundarapandian, V., Active controller design for generalized projective synchronization of four-scroll chaotic systems, International Journal of Systems Signal Control and Engineering Application, 2011, 4, 26-33.
54. Vaidyanathan, S., and Rasappan, S., Hybrid synchronization of hyperchaotic Qi and Lu systems by nonlinear control, Communications in Computer and Information Science, 2011, 131, 585-593.
55. Vaidyanathan, S., and Rajagopal, K., Hybrid synchronization of hyperchaotic Wang-Chen and hyperchaotic Lorenz systems by active non-linear control, International Journal of Systems Signal Control and Engineering Application, 2011, 4, 55-61.
56. Vaidyanathan, S., Output regulation of Arneodo-Coullet chaotic system, Communications in Computer and Information Science, 2011, 133, 98-107.
57. Sarasu, P., and Sundarapandian, V., The generalized projective synchronization of hyperchaotic Lorenz and hyperchaotic Qi systems via active control, International Journal of Soft Computing, 2011, 6, 216-223.
58. Vaidyanathan, S., and Pakiriswamy, S., The design of active feedback controllers for the generalized projective synchronization of hyperchaotic Qi and hyperchaotic Lorenz systems, Communications in Computer and Information Science, 2011, 245, 231-238.
59. Sundarapandian, V., and Karthikeyan, R., Hybrid synchronization of hyperchaotic Lorenz and hyperchaotic Chen systems via active control, Journal of Engineering and Applied Sciences, 2012, 7, 254-264.
60. Vaidyanathan, S., and Pakiriswamy, S., Generalized projective synchronization of double-scroll chaotic systems using active feedback control, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2012, 84, 111-118.
61. Pakiriswamy, S., and Vaidyanathan, S., Generalized projective synchronization of three-scroll chaotic systems via active control, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2012, 85, 146-155.
62. Karthikeyan, R., and Sundarapandian, V., Hybrid chaos synchronization of four-scroll systems via active control, Journal of Electrical Engineering, 2014, 65, 97-103.
63. Vaidyanathan, S., Azar, A. T., Rajagopal, K., and Alexander, P., Design and SPICE implementation of a 12-term novel hyperchaotic system and its synchronisation via active control, International Journal of Modelling, Identification and Control, 2015, 23, 267-277.
64. Yassen, M. T., Chaos synchronization between two different chaotic systems using active control, Chaos, Solitons and Fractals, 2005, 23, 131-140.
65. Jia, N., and Wang, T., Chaos control and hybrid projective synchronization for a class of new chaotic systems, Computers and Mathematics with Applications, 2011, 62, 4783-4795.
66. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of Lu and Pan systems by adaptive

nonlinear control, Communication in Computer and Information Science, 2011, 205, 193-202.

67. Vaidyanathan, S., Adaptive controller and synchronizer design for the Qi-Chen chaotic system, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunication Engineering, 2012, 85, 124-133.
68. Sundarapandian, V., Adaptive control and synchronization design for the Lu-Xiao chaotic system, Lectures on Electrical Engineering, 2013, 131, 319-327.
69. Vaidyanathan, S., Analysis, control and synchronization of hyperchaotic Zhou system via adaptive control, Advances in Intelligent Systems and Computing, 2013, 177, 1-10.
70. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of Lü and Pan systems by adaptive nonlinear control, Communications in Computer and Information Science, 2011, 205, 193-202.
71. Sundarapandian, V., and Karthikeyan, R., Anti-synchronization of Lü and Pan systems by adaptive nonlinear control, European Journal of Scientific Research, 2011, 64, 94-106.
72. Sundarapandian, V., and Karthikeyan, R., Anti-synchronization of hyperchaotic Lorenz and hyperchaotic Chen systems by adaptive control, International Journal of Systems Signal Control and Engineering Application, 2011, 4, 18-25.
73. Sundarapandian, V., and Karthikeyan, R., Adaptive anti-synchronization of uncertain Tigan and Li systems, Journal of Engineering and Applied Sciences, 2012, 7, 45-52.
74. Sarasu, P., and Sundarapandian, V., Generalized projective synchronization of three-scroll chaotic systems via adaptive control, European Journal of Scientific Research, 2012, 72, 504-522.
75. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of hyperchaotic Pang and hyperchaotic Wang systems via adaptive control, International Journal of Soft Computing, 2012, 7, 28-37.
76. Sarasu, P., and Sundarapandian, V., Generalized projective synchronization of two-scroll systems via adaptive control, International Journal of Soft Computing, 2012, 7, 146-156.
77. Sarasu, P., and Sundarapandian, V., Adaptive controller design for the generalized projective synchronization of 4-scroll systems, International Journal of Systems Signal Control and Engineering Application, 2012, 5, 21-30.
78. Vaidyanathan, S., Anti-synchronization of Sprott-L and Sprott-M chaotic systems via adaptive control, International Journal of Control Theory and Applications, 2012, 5, 41-59.
79. Vaidyanathan, S., and Pakiriswamy, S., Generalized projective synchronization of six-term Sundarapandian chaotic systems by adaptive control, International Journal of Control Theory and Applications, 2013, 6, 153-163.
80. Rasappan, S., and Vaidyanathan, S., Hybrid synchronization of n-scroll chaotic Chua circuits using adaptive backstepping control design with recursive feedback, Malaysian Journal of Mathematical Sciences, 2013, 7, 219-246.
81. Suresh, R., and Sundarapandian, V., Global chaos synchronization of a family of n-scroll hyperchaotic Chua circuits using backstepping control with recursive feedback, Far East Journal of Mathematical Sciences, 2013, 73, 73-95.
82. Rasappan, S., and Vaidyanathan, S., Hybrid synchronization of n-scroll Chua and Lur'e chaotic systems via backstepping control with novel feedback, Archives of Control Sciences, 2012, 22, 343-365.
83. Rasappan, S., and Vaidyanathan, S., Global chaos synchronization of WINDMI and Coullet chaotic systems using adaptive backstepping control design, Kyungpook Mathematical Journal, 2014, 54, 293-320.
84. Vaidyanathan, S., and Rasappan, S., Global chaos synchronization of n-scroll Chua circuit and Lur'e system using backstepping control design with recursive feedback, Arabian Journal for Science and Engineering, 2014, 39, 3351-3364.
85. Vaidyanathan, S., Idowu, B. A., and Azar, A. T., Backstepping controller design for the global chaos synchronization of Sprott's jerk systems, Studies in Computational Intelligence, 2015, 581, 39-58.
86. Vaidyanathan, S., Volos, C. K., Rajagopal, K., Kyprianidis, I. M., and Stouboulos, I. N., Adaptive backstepping controller design for the anti-synchronization of identical WINDMI chaotic systems with unknown parameters and its SPICE implementation, Journal of Engineering Science and Technology Review, 2015, 8, 74-82.
87. Vaidyanathan, S., and Sampath, S., Global chaos synchronization of hyperchaotic Lorenz systems by sliding mode control, Communications in Computer and Information Science, 2011, 205, 156-164.
88. Sundarapandian, V., and Sivaperumal, S., Sliding controller design of hybrid synchronization of four-wing chaotic systems, International Journal of Soft Computing, 2011, 6, 224-231.

89. Vaidyanathan, S., and Sampath, S., Anti-synchronization of four-wing chaotic systems via sliding mode control, International Journal of Automation and Computing, 2012, 9, 274-279.
90. Vaidyanathan, S., and Sampath, S., Sliding mode controller design for the global chaos synchronization of Coullet systems, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2012, 84, 103-110.
91. Vaidyanathan, S., and Sampath, S., Hybrid synchronization of hyperchaotic Chen systems via sliding mode control, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2012, 85, 257-266.
92. Vaidyanathan, S., Global chaos control of hyperchaotic Liu system via sliding control method, International Journal of Control Theory and Applications, 2012, 5, 117-123.
93. Vaidyanathan, S., Sliding mode control based global chaos control of Liu-Liu-Liu-Su chaotic system, International Journal of Control Theory and Applications, 2012, 5, 15-20.
94. Vaidyanathan, S., Global chaos synchronisation of identical Li-Wu chaotic systems via sliding mode control, International Journal of Modelling, Identification and Control, 2014, 22, 170-177.
95. Vaidyanathan, S., and Azar, A. T., Anti-synchronization of identical chaotic systems using sliding mode control and an application to Vaidyanathan-Madhavan chaotic systems, Studies in Computational Intelligence, 2015, 576, 527-547.
96. Vaidyanathan, S., and Azar, A. T., Hybrid synchronization of identical chaotic systems using sliding mode control and an application to Vaidyanathan chaotic systems, Studies in Computational Intelligence, 2015, 576, 549-569.
97. Vaidyanathan, S., Sampath, S., and Azar, A. T., Global chaos synchronisation of identical chaotic systems via novel sliding mode control method and its application to Zhu system, International Journal of Modelling, Identification and Control, 2015, 23, 92-100.
98. Li, H., Liao, X., Li, C., and Li, C., Chaos control and synchronization via a novel chatter free sliding mode control strategy, Neurocomputing, 2011, 74, 3212-3222.
99. Vaidyanathan, S., Adaptive synchronization of chemical chaotic reactors, International Journal of ChemTech Research, 2015, 8, 612-621.
100. Vaidyanathan, S., Adaptive control of a chemical chaotic reactor, International Journal of PharmTech Research, 2015, 8, 377-382.
101. Vaidyanathan, S., Dynamics and control of Brusselator chemical reaction, International Journal of ChemTech Research, 2015, 8, 740-749.
102. Vaidyanathan, S., Anti-synchronization of Brusselator chemical reaction systems via adaptive control, International Journal of ChemTech Research, 2015, 8, 759-768.
103. Vaidyanathan, S., Dynamics and control of Tokamak system with symmetric and magnetically confined plasma, International Journal of ChemTech Research, 2015, 8, 795-803.
104. Vaidyanathan, S., Synchronization of Tokamak systems with symmetric and magnetically confined plasma via adaptive control, International Journal of ChemTech Research, 2015, 8, 818-827.
105. Vaidyanathan, S., A novel chemical chaotic reactor system and its adaptive control, International Journal of ChemTech Research, 2015, 8, 146-158.
106. Vaidyanathan, S., Adaptive synchronization of novel 3-D chemical chaotic reactor systems, International Journal of ChemTech Research, 2015, 8, 159-171.
107. Vaidyanathan, S., Global chaos synchronization of chemical chaotic reactors via novel sliding mode control method, International Journal of ChemTech Research, 2015, 8, 209-221.
108. Garfinkel, A., Spano, M.L., Ditto, W.L., and Weiss, J.N., Controlling cardiac chaos, Science, 1992, 257, 1230-1235.
109. May, R.M., Simple mathematical models with very complicated dynamics, Nature, 261, 259-267.
110. Vaidyanathan, S., Adaptive backstepping control of enzymes-substrates system with ferroelectric behaviour in brain-waves, International Journal of PharmTech Research, 2015, 8, 256-261.
111. Vaidyanathan, S., Adaptive biological control of generalized Lotka-Volterra three species biological system, International Journal of PharmTech Research, 2015, 8, 622-631.
112. Vaidyanathan, S., 3-cells cellular neural network (CNN) attractor and its adaptive biological control, International Journal of PharmTech Research, 2015, 8, 632-640.
113. Vaidyanathan, S., Adaptive synchronization of generalized Lotka-Volterra three species biological systems, International Journal of PharmTech Research, 2015, 8, 928-937.
114. Vaidyanathan, S., Synchronization of 3-cells cellular neural network (CNN) attractors via adaptive control method, International Journal of PharmTech Research, 2015, 8, 946-955.

115. Vaidyanathan, S., Chaos in neurons and adaptive control of Birkhoff-Shaw strange chaotic attractor, International Journal of PharmTech Research, 2015, 8, 956-963.
116. Vaidyanathan, S., Adaptive chaotic synchronization of enzymes-substrates system with ferroelectric behaviour in brain waves, International Journal of PharmTech Research, 2015, 8, 964-973.
117. Vaidyanathan, S., Lotka-Volterra population biology models with negative feedback and their ecological monitoring, International Journal of PharmTech Research, 2015, 8, 974-981.
118. Vaidyanathan, S., Chaos in neurons and synchronization of Birkhoff-Shaw strange chaotic attractors via adaptive control, International Journal of PharmTech Research, 2015, 8, 1-11.
119. Vaidyanathan, S., Lotka-Volterra two species competitive biology models and their ecological monitoring, International Journal of PharmTech Research, 2015, 8, 32-44.
120. Vaidyanathan, S., Coleman-Gomatam logarithmic competitive biology models and their ecological monitoring, International Journal of PharmTech Research, 2015, 8, 94-105.
121. Vaidyanathan, S., Output regulation of the forced Van der Pol chaotic oscillator via adaptive control method, International Journal of PharmTech Research, 2015, 8, 106-116.
122. Vaidyanathan, S., Adaptive control of the FitzHugh-Nagumo chaotic neuron model, International Journal of PharmTech Research, 2015, 8, 117-127.
123. Vaidyanathan, S., Global chaos synchronization of the forced Van der Pol chaotic oscillators via adaptive control method, International Journal of PharmTech Research, 2015, 8, 156-166.
124. Vaidyanathan, S., Adaptive synchronization of the identical FitzHugh-Nagumo chaotic neuron models, International Journal of PharmTech Research, 2015, 8, 167-177.
125. Vaidyanathan, S., Global chaos synchronization of the Lotka-Volterra biological systems with four competitive species via active control, International Journal of PharmTech Research, 2015, 8, 206-217.
126. Pham, V.-T., Volos, C. K., Vaidyanathan, S., and Vu, V. Y., A memristor-based hyperchaotic system with hidden attractors: dynamics, synchronization and circuital emulating, Journal of Engineering Science and Technology Review, 2015, 8, 205-214.
127. Volos, C. K., Kyprianidis, I. M., Stouboulos, I. N., Tlelo-Cuautle, E., and Vaidyanathan, S., Memristor: A new concept in synchronization of coupled neuromorphic circuits, Journal of Engineering Science and Technology Review, 2015, 8, 157-173.
128. Pham, V.-T., Volos, C., Jafari, S., Wang, X., and Vaidyanathan, S., Hidden hyperchaotic attractor in a novel simple memristive neural network, Optoelectronics and Advanced Materials, Rapid Communications, 2014, 8, 1157-1163.
129. Volos, C. K., Pham, V.-T., Vaidyanathan, S., Kyprianidis, I. M., and Stouboulos, I. N., Synchronization phenomena in coupled Colpitts circuits, Journal of Engineering Science and Technology Review, 2015, 8, 142-151.
130. Frohlich, H., Long range coherence and energy storage in biological systems, International Journal of Quantum Chemistry, 1968, 2, 641-649.
131. Kaiser, F., Coherent oscillations in biological systems, I. Bifurcation phenomena and phase transitions in an enzyme–substrate reaction with ferroelectric behavior, Z. Naturforsch A, 1978, 294, 304–333.
132. Enjieu Kadji, H.G., Chabi Orou, J.B., Yamapi, R., and Woafo, P., Nonlinear dynamics and strange attractors in the biological system, Chaos, Solitons and Fractals, 2007, 32, 862-882.
133. Nagrath, I. J., and Gopal, M., Control Systems Engineering, 5th Edition, New Age Publishers, New Delhi, India, 2009.

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