A New 4-D Hyperchaotic System with a Two-Scroll Attractor, its Adaptive Control and Circuit Simulation

Sundarapandian Vaidyanathan
Research and Development Centre
Vel Tech University
Chennai, Tamil Nadu, India
sundarvtu@gmail.com

Aceng Sambas
Department of Mechanical Engineering
Universitas Muhammadiyah Tasikmalaya
Tasikmalaya, Indonesia
acengs@umtas.ac.id

Sukono
Department of Mathematics,
Faculty of Mathematics and Natural Sciences
Universitas Padjadjaran, Indonesia.
sukono@unpad.ac.id

Subiyanto
Department of Marine Science
Universitas Padjadjaran, Indonesia.
subiyanto@unpad.ac.id

Mustafa Mamat
Faculty of Informatics and Computing
Universiti Sultan Zainal Abidin
Kuala Terengganu, Malaysia
must@unisza.edu.my

Abdul Talib Bon
Department of Production and Operations
University Tun Hussein Onn Malaysia, Malaysia
talibon@gmail.com

Abstract

In the chaos literature, there is great interest in the modelling of hyperchaotic systems. This paper announces a new 4-D hyperchaotic system with a two-scroll attractor. The phase portraits and qualitative properties of the new hyperchaotic system are explored with MATLAB plots, bifurcation diagram, Lyapunov exponents, Kaplan-Yorke dimension, etc. As a control application, the adaptive stabilization of the new hyperchaotic system is detailed using Lyapunov stability theory. Finally, an electronic circuit of the new hyperchaotic system with MultiSIM is designed and a good match between the plots of the theoretical model and the circuit model of the new hyperchaotic system is shown.

Keywords
Hyperchaos, hyperchaotic systems, adaptive control, stabilization and electronic circuit.

1. Introduction

Chaos theory deals with chaotic systems which are nonlinear dynamical systems highly sensitive to small changes in the initial conditions (Azar and Vaidyanathan, 2016; Vaidyanathan and Volos, 2016). Chaos theory has several applications in science and engineering such as memristors (Vaidyanathan and Volos, 2017), weather systems (Lorenz, 1963; Vaidyanathan *et al.* 2015), biological systems (Vaidyanathan 2015a, 2015b, 2015c, 2015d, Voorsluijs and Decker, 2016), neural systems (Vaidyanathan 2015e, 2015f, 2015g, 2015h), oscillators (Pakiriswamy and Vaidyanathan, 2012; Rasappan and Vaidyanathan, 2012; Vaidyanathan 2012a, 2012b, 2014, 2015i, 2015j; Vaidyanathan and Pakiriswamy, 2011, 2012; Vaidyanathan and Rasappan, 2011; Vaidyanathan and Sampath, 2012), chemical reactors (Vaidyanathan, 2015k), circuits (Li *et al*., 2014, 2015; Daltzis *et al*., 2018; Mamat *et al*., 2018; Pham *et al*., 2016; Sambas *et al*., 2018a, 2018b; Vaidyanathan, 2018a, 2018b, 2018c, 2018d, 2018e), finance (Tacha *et al.,* 2016), robotics (Sambas *et al*., 2016; Vaidyanathan *et al.* 2017), etc.

Hyperchaotic systems are chaotic systems having two or more positive Lyapunov exponents, which means that the state evolution for hyperchaotic systems can expand in two or more directions yielding high complexity (Azar and Vaidyanathan, 2016; Vaidyanathan and Volos, 2016). Hyperchaotic systems are suitable for many engineering applications such as steganography (Vaidyanathan *et al.,* 2018f), cryptography (Murali, 2000; Wu *et al.,* 2014), image encryption (Xue *et al.,* 2018), secure communications (Li *et al*., 2005), etc.

This work announces a new 4-D hyperchaotic system with a two-scroll attractor. It is interesting to know that the new hyperchaotic system has only two quadratic nonlinearities and it has two positive Lyapunov exponents confirming its hyperchaotic behavior. We show that the new hyperchaotic system has an unstable, saddle-point, equilibrium at the origin. We describe the dynamic properties of the new hyperchaotic system via phase plots, Lyapunov exponents, Kaplan-Yorke dimension, etc. As a control application, we build an adaptive feedback control law for globally stabilizing the trajectories of the new hyperchaotic system. Finally, an electronic circuit of the new hyperchaotic system with two-scroll attractor is designed via MultiSIM to verify the feasibility of the theoretical model. Our simulations show a good match between the MATLAB plots and the MultiSIM simulations of the new hyperchaotic system with a two-scroll attractor.

2. A New 4-D Hyperchaotic System with a Two-Scroll Attractor

In this work, we report a new 4-D system given by the dynamics

$$\begin{cases} \dot{x}_1 = a(x_2 - x_1) + x_4 \\ \dot{x}_2 = bx_1 - x_2 - dx_1x_3 + x_4 \\ \dot{x}_3 = x_1x_2 - cx_3 \\ \dot{x}_4 = -x_1 - x_2 \end{cases} \tag{1}$$

In (1), $X = (x_1, x_2, x_3, x_4)$ is the state and a, b, c, d are constant parameters. We shall show that the system (1) exhibits a hyperchaotic two-scroll attractor for the parameter values

$$a = 12, \quad b = 40, \quad c = 5, \quad d = 12 \tag{2}$$

The Lyapunov exponents of the new system (1) for $(a, b, c, d) = (12, 40, 5, 12)$ and $X(0) = (0.2, 0.2, 0.2, 0.2)$ are calculated for $T = 10^5$ seconds using Wolf's algorithm (Wolf *et al.,* 1985) as follows:

$$LE_1 = 1.0905, \quad LE_2 = 0.1278, \quad LE_3 = 0, \quad LE_4 = -19.1710 \tag{3}$$

From (3), we note that the new 4-D system (1) is hyperchaotic since it has two positive Lyapunov exponents. Also, the new system (1) is dissipative since the sum of the Lyapunov exponents is negative.

Furthermore, the Kaplan-Yorke dimension of the new system (1) is determined as follows:

$$D_{KY} = 3 + \frac{LE_1 + LE_2 + LE_3}{|LE_4|} = 3.0635 \tag{4}$$

The value of the Kaplan-Yorke dimension obtained in (4) shows the high complexity of the new hyperchaotic system (4), which is dissipative with a strange attractor.

We note that the new hyperchaotic system (1) remains invariant under the change of coordinates given by

$$(x_1, x_2, x_3, x_4) \mapsto (-x_1, -x_2, x_3, -x_4) \tag{5}$$

This shows that the new hyperchaotic system (1) has rotation symmetry about the x_3 – coordinate axis. Hence, all the non-trivial trajectories of the new hyperchaotic system (1) must have twin trajectories associated with them.

We get the equilibrium points of the new hyperchaotic system (1) by solving the following equations for the hyperchaotic case $(a,b,c,d) = (12,40,5,12)$:

$$a(x_2 - x_1) + x_4 = 0 \tag{6a}$$
$$bx_1 - x_2 - dx_1x_3 + x_4 = 0 \tag{6b}$$
$$x_1x_2 - cx_3 = 0 \tag{6c}$$
$$-x_1 - x_2 = 0 \tag{6d}$$

Solving the system (6), it is easy to see that the unique equilibrium of the new hyperchaotic system (1) is given by $E_0 = (0,0,0,0)$.

The Jacobian of the new hyperchaotic system (1) at E_0 for $(a,b,c,d) = (12,40,5,12)$ is obtained as follows.

$$J = \begin{bmatrix} -12 & 12 & 0 & 1 \\ -40 & -1 & 0 & 1 \\ 0 & 0 & -5 & 0 \\ -1 & -1 & 0 & 0 \end{bmatrix} \tag{7}$$

The eigenvalues of J are obtained as $\lambda_1 = 0.0303,\ \lambda_2 = -5,\ \lambda_{3,4} = -6.5152 \pm 21.2591i.$

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

Hence, the strange attractor associated with the new hyperchaotic system (1) is a self-excited attractor.

The phase plots of the new hyperchaotic system (1) for $X(0) = (0.2, 0.2, 0.2, 0.2)$ and $(a,b,c,d) = (12,40,5,12)$ are shown in Figures 1-4. From the phase plots, the new hyperchaotic system (1) has a two-scroll hyperchaotic attractor. Also, Figure 5 shows the Lyapunov exponents of the new hyperchaotic system (1). The presence of two positive Lyapunov exponents in Figure 5 confirms that the new 4-D system (1) is indeed a hyperchaotic system.

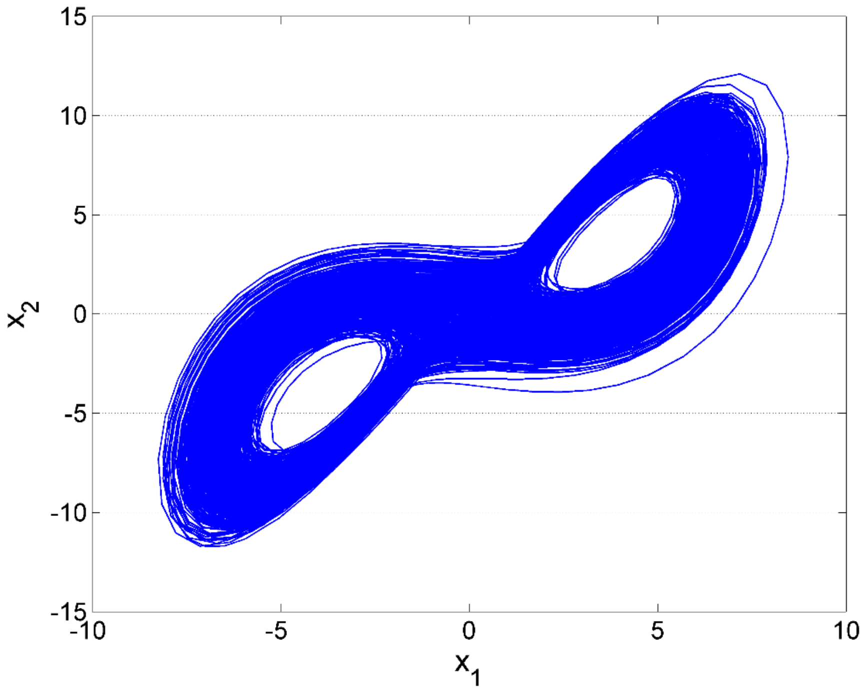

Figure 1. 2-D phase plot of the new hyperchaotic system (1) in the $(x_1, x_2)-$plane for $X(0) = (0.2, 0.2, 0.2, 0.2)$ and $(a, b, c, d) = (12, 40, 5, 12)$

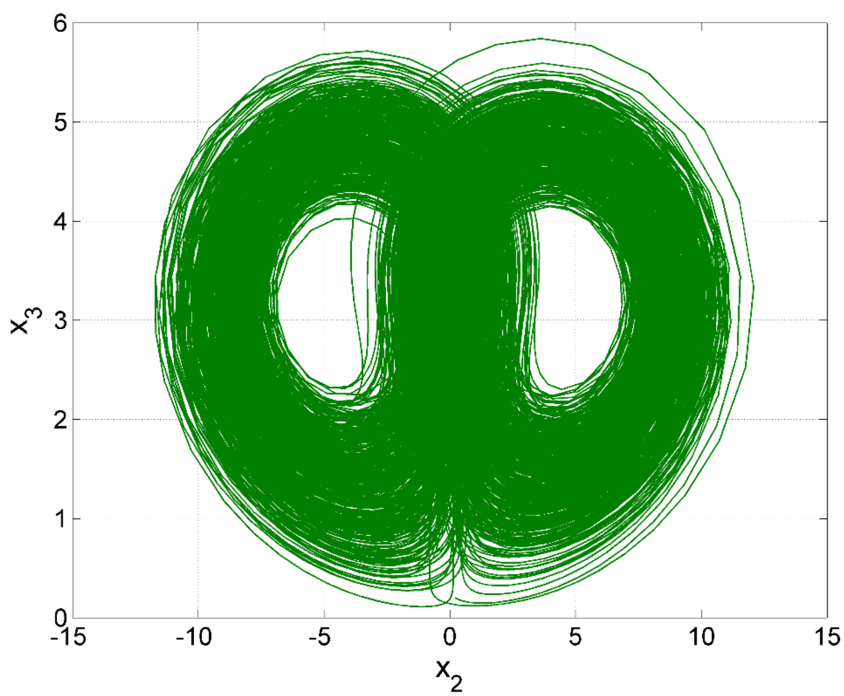

Figure 2. 2-D phase plot of the new hyperchaotic system (1) in the $(x_2, x_3)-$plane for $X(0) = (0.2, 0.2, 0.2, 0.2)$ and $(a, b, c, d) = (12, 40, 5, 12)$

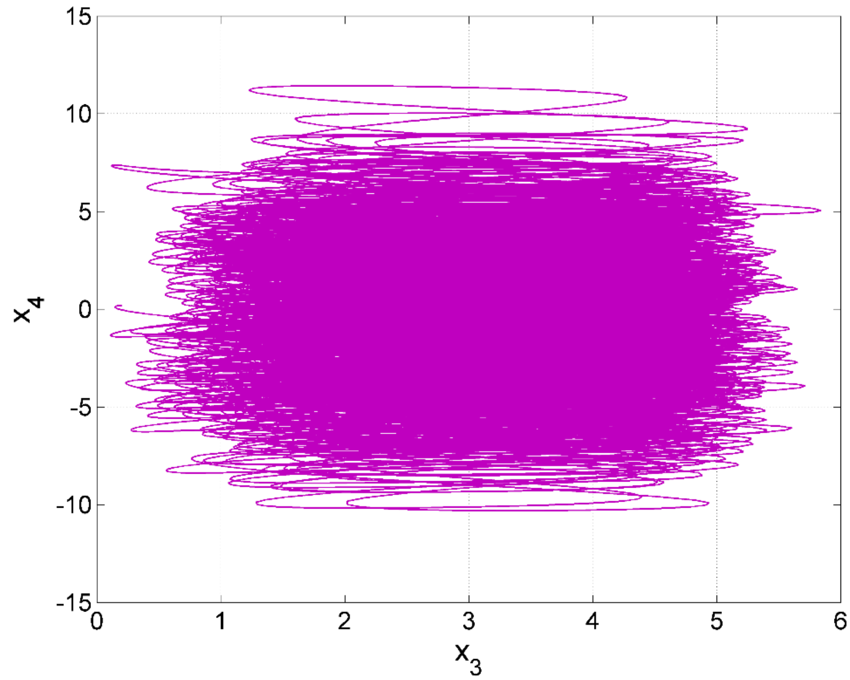

Figure 3. 2-D phase plot of the new hyperchaotic system (1) in the $(x_3, x_4)-$plane for $X(0) = (0.2, 0.2, 0.2, 0.2)$ and $(a, b, c, d) = (12, 40, 5, 12)$

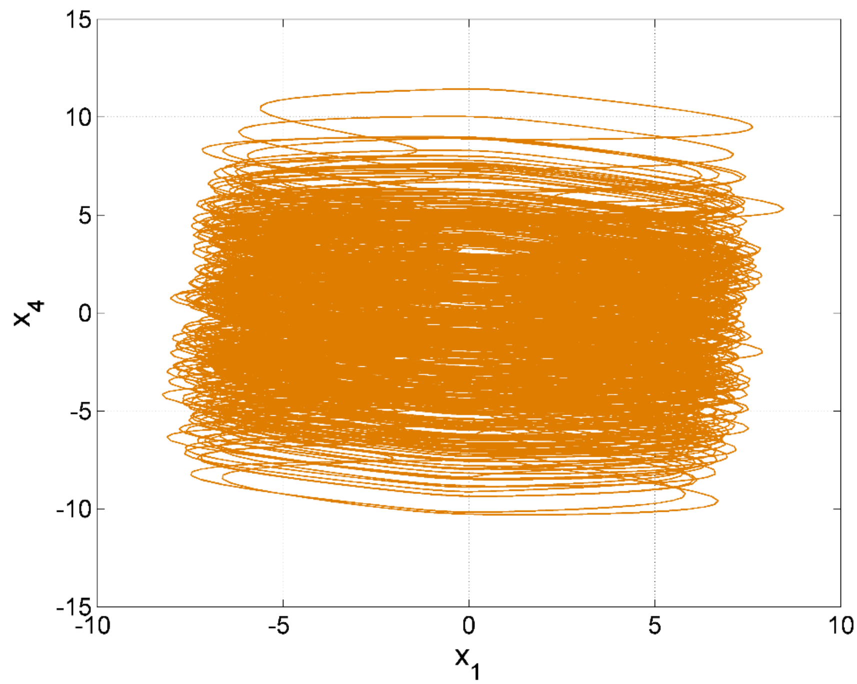

Figure 4. 2-D phase plot of the new hyperchaotic system (1) in the $(x_1, x_4)-$plane for $X(0) = (0.2, 0.2, 0.2, 0.2)$ and $(a, b, c, d) = (12, 40, 5, 12)$

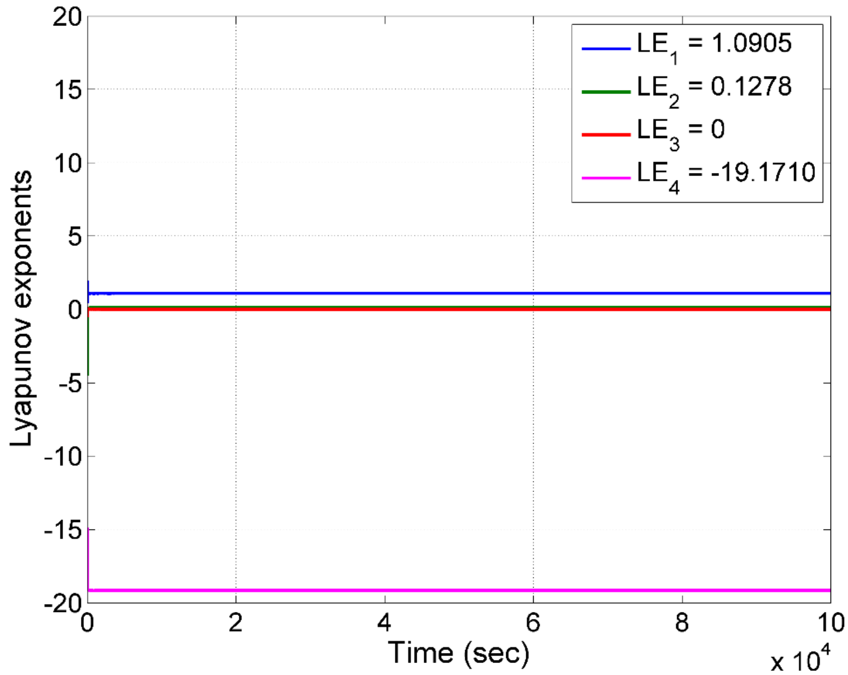

Figure 5. Lyapunov exponents of the new system (1) for $X(0)=(0.2,0.2,0.2,0.2)$ and $(a,b,c,d)=(12,40,5,12)$

3. Global Chaos Control of the New 4-D Hyperchaotic System with a Two-Scroll Attractor

In this section, we consider the problem of globally stabilizing the trajectories of the new 4-D hyperchaotic system, which is given by the controlled dynamics

$$\begin{cases} \dot{x}_1 = a(x_2 - x_1) + x_4 + u_1 \\ \dot{x}_2 = bx_1 - x_2 - dx_1x_3 + x_4 + u_2 \\ \dot{x}_3 = x_1x_2 - cx_3 + u_3 \\ \dot{x}_4 = -x_1 - x_2 + u_4 \end{cases} \tag{8}$$

In (8), $X=(x_1,x_2,x_3,x_4)$ is the state, $\boldsymbol{u}=(u_1,u_2,u_3,u_4)$ is the adaptive control to be designed and a,b,c,d are system parameters which are not available for measurement. So, we use estimates $A(t),B(t),C(t),D(t)$ in lieu of the unknown system parameters a,b,c,d, respectively.

We consider the adaptive control given by

$$\begin{cases} u_1 = -A(t)(x_2 - x_1) - x_4 - k_1x_1 \\ u_2 = -B(t)x_1 + x_2 + D(t)x_1x_3 - x_4 - k_2x_2 \\ u_3 = -x_1x_2 + C(t)x_3 - k_3x_3 \\ u_4 = x_1 + x_2 - k_4x_4 \end{cases} \tag{9}$$

In (9), k_1,k_2,k_3,k_4 are positive constants, and $A(t),B(t),C(t),D(t)$ are parameter estimates. We define the parameter estimation error as follows:

$$\begin{cases} e_a = a - A(t) \\ e_b = b - B(t) \\ e_c = c - C(t) \end{cases} \tag{10}$$

Differentiating (10), we obtain the following:

$$\begin{cases} \dot{e}_a = -\dot{A}(t) \\ \dot{e}_b = -\dot{B}(t) \\ \dot{e}_c = -\dot{C}(t) \end{cases} \tag{11}$$

By substituting the adaptive control law (9) into (8), we get the closed-loop state dynamics as follows:

$$\begin{cases} \dot{x}_1 = [a - A(t)](x_2 - x_1) - k_1 x_1 \\ \dot{x}_2 = [b - B(t)]x_1 - [d - D(t)]x_1 x_3 - k_2 x_2 \\ \dot{x}_3 = -[c - C(t)]x_3 - k_3 x_3 \\ \dot{x}_4 = -k_4 x_4 \end{cases} \tag{12}$$

Using the definition (10), it is possible to simplify the closed-loop dynamics (12) as follows:

$$\begin{cases} \dot{x}_1 = e_a (x_2 - x_1) - k_1 x_1 \\ \dot{x}_2 = e_b x_1 - e_d x_1 x_3 - k_2 x_2 \\ \dot{x}_3 = -e_c x_3 - k_3 x_3 \\ \dot{x}_4 = -k_4 x_4 \end{cases} \tag{13}$$

We consider the quadratic Lyapunov function V defined as follows:

$$V(X, e_a, e_b, e_c, e_d) = \frac{1}{2}\left(x_1^2 + x_2^2 + x_3^2 + x_4^2\right) + \frac{1}{2}\left(e_a^2 + e_b^2 + e_c^2 + e_d^2\right) \tag{14}$$

Differentiating V along the trajectories of (13) and (11), we obtain the following:

$$\dot{V} = -\sum_{i=1}^{4} k_i e_i^2 + e_a\left[x_1(x_2 - x_1) - \dot{A}\right] + e_b\left[x_1 x_2 - \dot{B}\right] + e_c\left[-x_3^2 - \dot{C}\right] + e_d\left[-x_1 x_2 x_3 - \dot{D}\right] \tag{15}$$

In view of (15), we propose the following parameter update law:

$$\begin{cases} \dot{A} = x_1(x_2 - x_1) \\ \dot{B} = x_1 x_2 \\ \dot{C} = -x_3^2 \\ \dot{D} = -x_1 x_2 x_3 \end{cases} \tag{16}$$

Thus, we prove the following main result of this section.

The new result is established using Lyapunov stability theory (Khalil, 2002).

Theorem 1. The new hyperchaotic two-scroll system (8) with unknown system parameters a,b,c,d is globally stabilized for all initial conditions $X(0) \in R^4$ with the adaptive feedback control law (9) and the parameter update law (16), where the control gains k_1, k_2, k_3, k_4 are positive constants.

Proof. First, we note that the candidate Lyapunov function V given in Eq. (14) is a quadratic and positive definite function defined on R^8. Next, we substitute the parameter update law (16) into Eq. (15). This yields the following:

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

This shows that $\dot{V}$ is a negative semi-definite function on R^8. Hence, by Barbalat's Lemma (Khalil, 2002), we conclude that the controlled state $x_i(t), (i = 1,2,3,4)$ of the closed-loop system (13) exponentially converges to zero as $t \to \infty$. This completes the proof. ■

For numerical simulations, we take the control gains as $k_i = 8$ for $i = 1,2,3,4$. Also, we take the parameter values as in the hyperchaotic case (2), *i.e.* $(a,b,c,d) = (12,40,5,12)$.

As the initial state, we take $X(0) = (1.5,\ 8.3,\ 4.1,\ 9.7)$. As the initial state for the parameter estimate, we take $(A(0), B(0), C(0), D(0)) = (8,\ 4,\ 5,\ 2)$.

Figure 6 shows the time-history of the state $X(t)$ of the controlled hyperchaotic two-scroll system (8), when the adaptive feedback control law (9) and the parameter update law (16) are implemented.

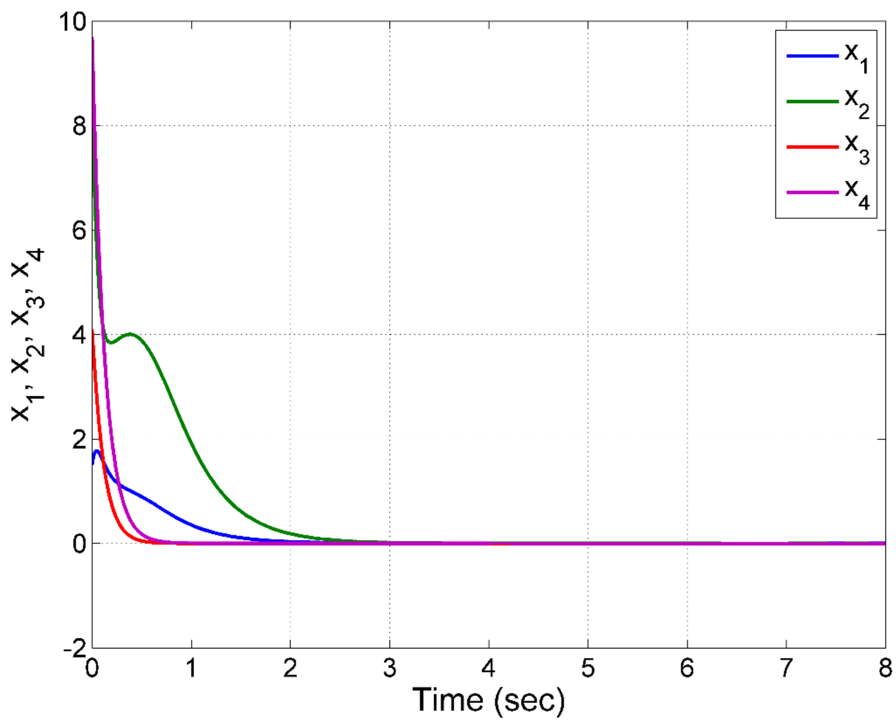

Figure 6. Time-history of the state $X(t)$ of the controlled system (8)

4. Circuit Simulation of the New 4-D Hyperchaotic System with a Two-Scroll Attractor

In this section, electronic circuit of the hyperchaotic system (1) is implemented. Figure 7 presents the schematic diagram of the proposed analog simulator for hyperchaotic system (1). According to Kirchhoff's circuit laws, the equations in terms of the circuit parameters are:

$$\begin{cases} \dot{x}_1 = \dfrac{1}{C_1R_1}x_2 - \dfrac{1}{C_1R_2}x_1 + \dfrac{1}{C_1R_3}x_4 \\ \dot{x}_2 = \dfrac{1}{C_2R_4}x_1 - \dfrac{1}{C_2R_5}x_2 - \dfrac{1}{10C_2R_6}x_1x_3 + \dfrac{1}{C_2R_7}x_4 \\ \dot{x}_3 = \dfrac{1}{10C_3R_8}x_1x_2 - \dfrac{1}{C_3R_9}x_3 \\ \dot{x}_4 = -\dfrac{1}{C_4R_{10}}x_1 - \dfrac{1}{C_4R_{11}}x_2 \end{cases} \tag{18}$$

In (18), x_1, x_2, x_3 and x_4 correspond to the voltages on the integrators U1A, U2A, U3A and U4A, respectively. The values of the circuit components are chosen as: $R_1 = R_2 = 33.33\text{k}\Omega$, $R_3 = R_5 = R_7 = R_{10} = R_{11} = 400\ \text{k}\Omega$, $R_4 = 10\ \text{k}\Omega$, $R_6 = 3.33\ \text{k}\Omega$, $R_8 = 40\ \text{k}\Omega$, $R_9 = 80\ \text{k}\Omega$, $R_{12} = R_{13} = R_{14} = R_{15} = R_{16} = R_{17} = 100\ \text{k}\Omega$, $C_1 = C_2 = C_3 = C_4 = 1$ nF. Phase potraits from the output of the integration channels are given in Figure 8. We notice a very good similarity between numerical simulations (see Figures 1-4) and oscilloscope results (see Figure 8).

5. Conclusions

In this paper, we proposed a new 4-D hyperchaotic system with a two-scroll attractor. Lyapunov exponents are derived to prove that the system is hyperchaotic. Also, the numerical simulation and electronic circuit design of a new 4-D hyperchaotic system with a two-scroll attractor are fulfilled. As a control application, we devised adaptive control law for globally stabilizing all the trajectories of the new hyperchaotic system with a two-scroll attractor. Hyperchaotic systems have several applications in engineering areas such as cryptography, encryption, secure communications, etc. It is hoped that the new hyperchaotic system is applied to many engineering areas.

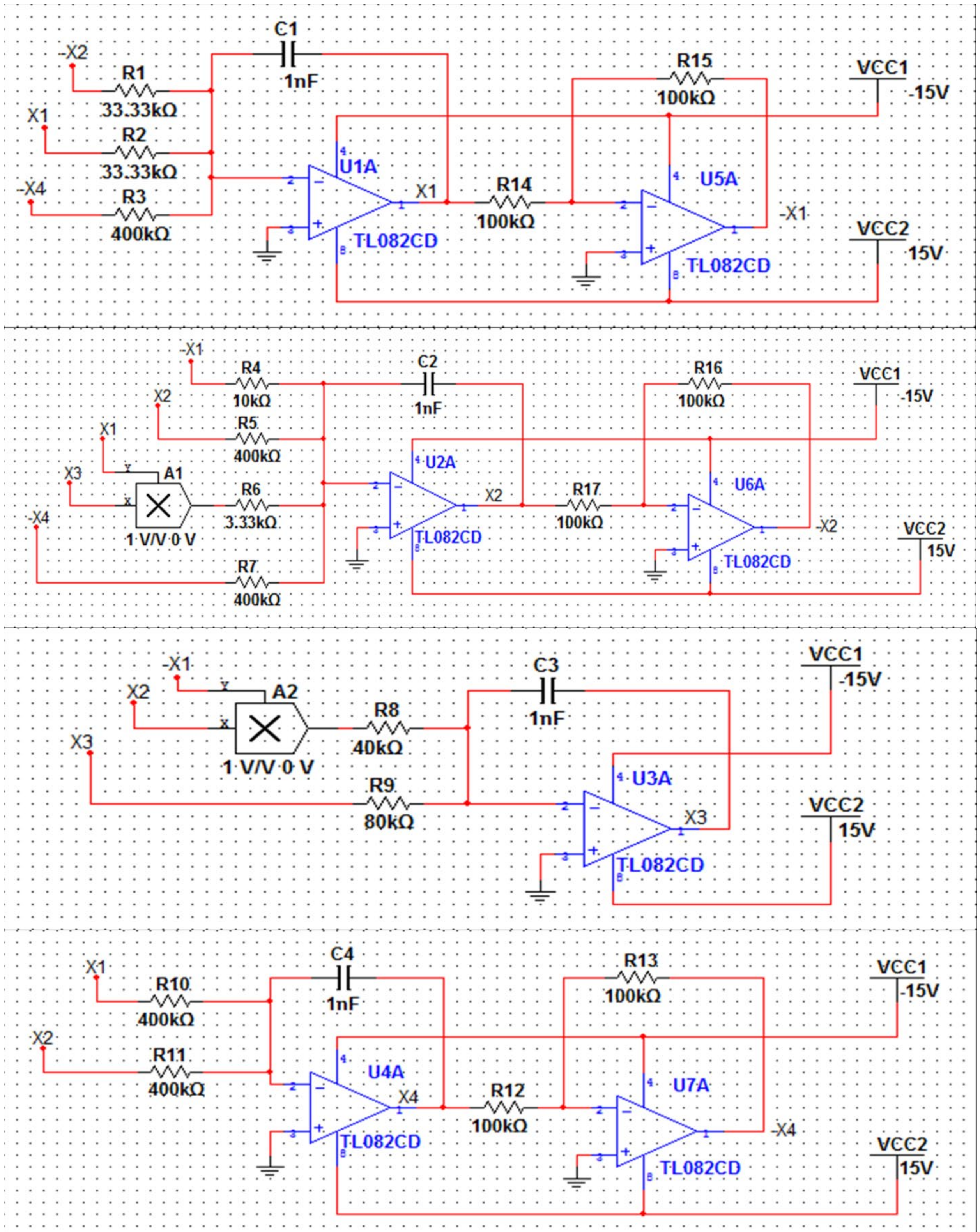
C1
1nF
-X2
R1
33.33kΩ
X1
R2
33.33kΩ
-X4
R3
400kΩ
U1A
TL082CD
X1
R14
100kΩ
R15
100kΩ
U5A
TL082CD
-X1
VCC1
-15V
VCC2
15V
-X1
R4
10kΩ
C2
1nF
X2
R5
400kΩ
X1
X3
A1
1 V/V 0 V
R6
3.33kΩ
-X4
R7
400kΩ
U2A
TL082CD
X2
R16
100kΩ
R17
100kΩ
U6A
TL082CD
-X2
VCC1
-15V
VCC2
15V
-X1
X2
A2
1 V/V 0 V
R8
40kΩ
C3
1nF
X3
R9
80kΩ
U3A
TL082CD
X3
VCC1
-15V
VCC2
15V
X1
R10
400kΩ
C4
1nF
X2
R11
400kΩ
U4A
TL082CD
X4
R12
100kΩ
R13
100kΩ
U7A
TL082CD
-X4
VCC1
-15V
VCC2
15V

Figure 7. The electronic circuit schematic of the new 4-D hyperchaotic system with a two-scroll attractor

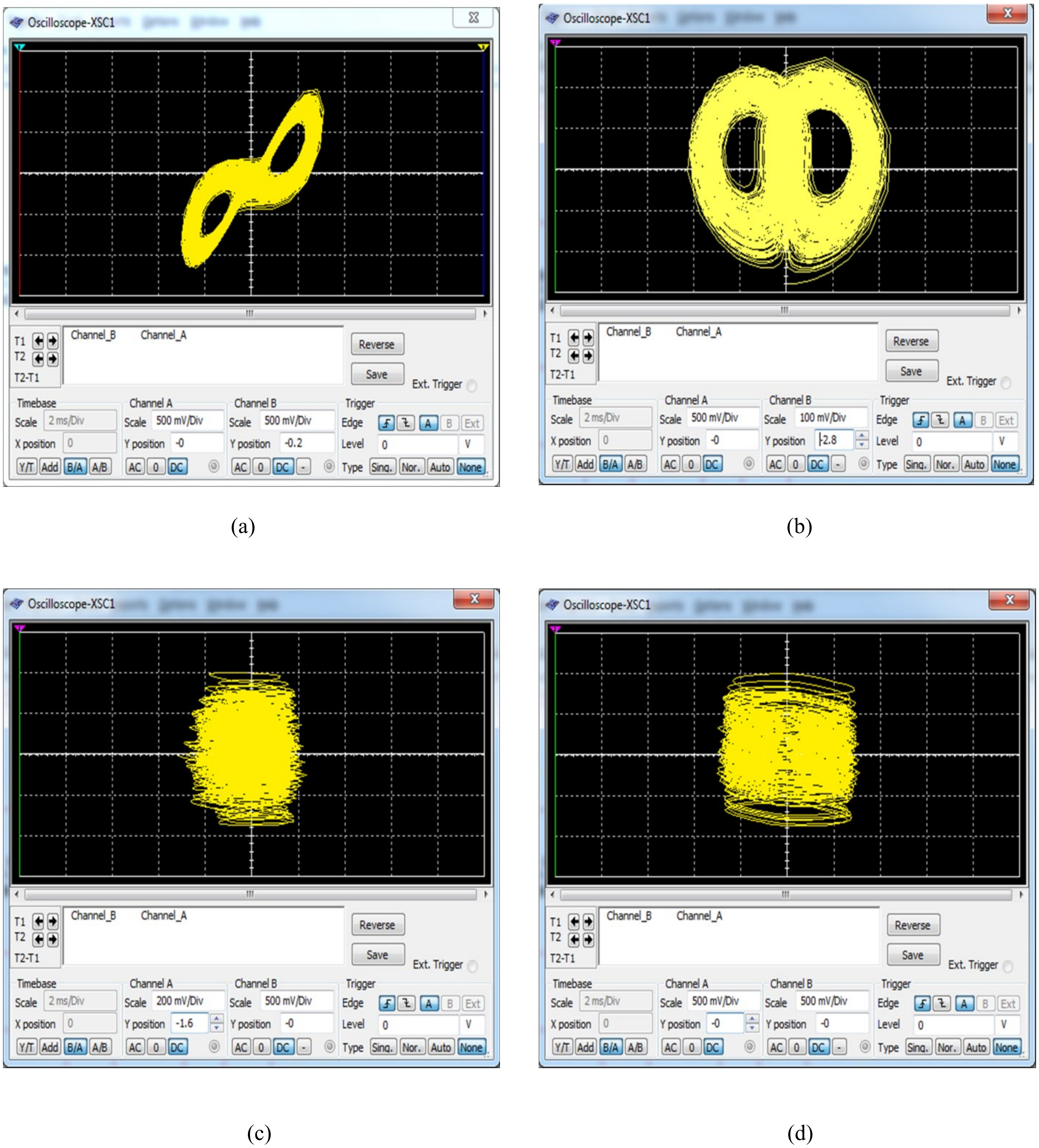

Figure 8 MultiSIM chaotic attractors of the new 4-D hyperchaotic system with a two-scroll attractor (a) x_1- x_2 plane, (b) x_2- x_3 plane, (c) x_3- x_4 plane and (d) x_1- x_4 plane.

References

Azar, A.T., and Vaidyanathan, S., *Advances in Chaos Theory and Intelligent Control*, Springer, Berlin, 2016.

Daltzis, P., Vaidyanathan, S., Pham, V.T., Volos, C., Nistazakis, E., and Tombras, G., Hyperchaotic attractor in a novel hyperjerk system with two nonlinearities, *Circuits, Systems, and Signal Processing*, vol. 37, no. 2, pp. 613-635, 2018.

Khalil, H.K., *Nonlinear Systems*, Prentice Hall, New York, 2002.

Li, C., Liao, X., and Wong, K.W., Lag synchronization of hyperchaos with application to secure communications, *Chaos, Solitons and Fractals*, vol. 23, no. 1, pp. 183-193, 2005.

Li, C., Sprott, J. C., Thio, W and Zhu, H. A new piecewise linear hyperchaotic circuit. *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 61, no. 12, 977-981, 2014.

Li, H., Li, C., Yuan, Z., Hu, W and Zhen, X. A new class of chaotic circuit with logic elements. *Journal of Circuits, Systems and Computers*, vol. 24, no. 9, 1550136, 2015.

Lorenz, E.N., Deterministic nonperiodic flow, *Journal of the Atmospheric Sciences*, vol. 20, pp. 130-141, 1963.

Mamat, M., Vaidyanathan, S., Sambas, A., Mohamed, M.A., Sampath, S., and Sanjaya, W.S.M., A New 3-D chaotic system with conch-shaped equilibrium curve and its circuit implementation, *International Journal of Engineering and Technology*, vol. 7, no. 3, pp. 1410-1414, 2018.

Murali, K., Heterogeneous chaotic systems based cryptography, *Physics Letters A*, vol. 272, pp. 184-192, 2000.

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*, vol. 85, pp. 146-155, 2012.

Pham, V.T., Jafari, S., Volos, C., Giakoumis, A., and Vaidyanathan, S., A chaotic system with equilibria located on the rounded square loop and its circuit implementation, *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 63, no. 9, pp. 878-882, 2016.

Rasappan, S., and Vaidyanathan, S., "Synchronization of hyperchaotic Liu system via backstepping control with recursive feedback, *Communications in Computer and Information Science*, vol. 305, pp. 212-221, 2012.

Sambas, A., Vaidyanathan, S., Mamat, M., Sanjaya, W.S.M., and Rahayu, D.S., A 3-D novel jerk chaotic system and its application in secure communication system and mobile robot navigation, *Studies in Computational Intelligence*, vol. 636, pp. 283-310, 2016.

Sambas, A., Mamat, M., Vaidyanathan, S., Mohamed, M.A., and Mada Sanjaya, W.S., A new 4-D chaotic system with hidden attractor and its circuit implementation, *International Journal of Engineering and Technology*, vol. 7, no. 3, pp. 1245-1250, 2018a.

Sambas, A., Mamat, M., Vaidyanathan, S., Mohamed, M.A., Mada Sanjaya, W.S., and Mujiarto, A novel chaotic hidden attractor, its synchronization and circuit implementation, *WSEAS Transactions on Systems and Control*, vol. 13, pp. 345-352, 2018b.

Tacha, O.I., Volos, C.K., Kyprianidis, I.M., Stouboulos, I.N., Vaidyanathan, S., and Pham, V.T., Analysis, adaptive control and circuit simulation of a novel nonlinear finance system, *Applied Mathematics and Computation*, vol. 276, pp. 200-217, 2016.

Vaidyanathan, S., Adaptive controller and synchronizer design for the Qi-Chen chaotic system, *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering*, vol. 85, pp. 124-133, 2012a.

Vaidyanathan, S., Analysis and synchronization of the hyperchaotic Yujun systems via sliding mode control, *Advances in Intelligent Systems and Computing,* vol. 176, pp. 329-337, 2012b.

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*, vol. 7, no. 1, pp.1-20, 2014.

Vaidyanathan, S., Output regulation of the forced Van der Pol chaotic oscillator via adaptive control method, *International Journal of PharmTech Research*, vol. 8, no. 6, pp. 106-116, 2015a.

Vaidyanathan, S., Global chaos synchronization of the forced Van der Pol chaotic oscillators via adaptive control method, *International Journal of PharmTech Research*, vol. 8, no. 6, pp. 156-166, 2015b.

Vaidyanathan, S., Global chaos synchronization of the Lotka-Volterra biological systems with four competitive species via active control, *International Journal of PharmTech Research*, vol. 8, no. 6, pp. 206-207, 2015c.

Vaidyanathan, S., Lotka-Volterra population biology models with negative feedback and their ecological monitoring, *International Journal of PharmTech Research*, vol. 8, no. 5, pp. 974-981, 2015d.

Vaidyanathan, S., Synchronization of 3-cells cellular neural network (CNN) attractors via adaptive control method, *International Journal of PharmTech Research*, vol. 8, no. 5, pp. 946-955, 2015e.

Vaidyanathan, S., Adaptive control of the FitzHugh-Nagumo chaotic neuron model, *International Journal of PharmTech Research*, vol. 8, no. 6, pp. 117-127, 2015f.

Vaidyanathan, S., Chaos in neurons and synchronization of Birkhoff-Shaw strange chaotic attractors via adaptive control, *International Journal of PharmTech Research*, vol. 8, no. 6, pp. 1-11, 2015g.

Vaidyanathan, S., Adaptive synchronization of the identical FitzHugh-Nagumo chaotic neuron models, *International Journal of PharmTech Research*, vol. 8, no. 6, pp. 167-177, 2015h.

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*, vol. 23, no. 4, pp.380-392, 2015i.

Vaidyanathan, S., Analysis, control, and synchronization of a 3-D novel jerk chaotic system with two quadratic nonlinearities, *Kyungpook Mathematical Journal*, vol. 55, no. 3, pp. 563-586, 2015j.

Vaidyanathan, S., Global chaos synchronization of chemical chaotic attractors via novel sliding mode control method, *International Journal of ChemTech Research*, vol. 8, no. 7, pp. 209-221, 2015k.

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*, vol. 245, pp. 231-238, 2011.

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*, vol. 84, pp. 111-118, 2012.

Vaidyanathan, S., and Rasappan, S., Hybrid synchronization of hyperchaotic Qi and Lü systems by nonlinear control, *Communications in Computer and Information Science*, vol. 131, pp. 585-593, 2011.

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*, vol. 84, pp. 103-110, 2012.

Vaidyanathan, S., and Volos, C., *Advances and Applications in Chaotic Systems*, Springer, Berlin, 2016.

Vaidyanathan, S., and Volos, C., *Advances in Memristors, Memristive Devices and Systems,* Springer, Berlin, 2017.

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 and Technology Review*, vol. 8, no. 2, pp. 74-82, 2015.

Vaidyanathan, S., Sambas, A., Mamat, M., Sanjaya WS, M., A new three-dimensional chaotic system with a hidden attractor, circuit design and application in wireless mobile robot, *Archives of Control Sciences*, vol. 27, no. 4, 2017.

Vaidyanathan, S., Azar, A.T., Rajagopal, K., Sambas, A., Kacar, S., and Cavusoglu, U., A new hyperchaotic temperature fluctuations model, its circuit simulation, FPGA implementation and an application to image encryption, *International Journal of Simulation and Process Modelling*, vol. 13, no. 3, pp. 281-296, 2018a.

Vaidyanathan, S., Jafari, S., Pham, V.T., Azar, A.T., and Alsaadi, F.E., A 4-D chaotic hyperjerk system with a hidden attractor, adaptive backstepping control and circuit design, *Archives of Control Sciences*, vol. 28, no. 2, pp. 239-254, 2018b.

Vaidyanathan, S., Sambas, A., Kacar, S., and Cavusoglu, U., A new three-dimensional chaotic system with a cloud-shaped curve of equilibrium points, its circuit implementation and sound encryption, *International Journal of Modelling, Identification and Control*, vol. 30, no. 3, pp. 184-196, 2018c.

Vaidyanathan, S., Sambas, A., Mohamed, M.A., Mamat, M., and Mada Sanjaya, W.S., A new hyperchaotic hyperjerk system with three nonlinear terms, its synchronization and circuit simulation, *International Journal of Engineering and Technology*, vol. 7, no. 3, pp. 1585-1592, 2018d.

Vaidyanathan, S., Feki, M., Sambas, A., and Lien, C.H., A new biological snap oscillator: Its modelling, analysis, simulations and circuit design, *International Journal of Simulation and Process Modelling*, vol. 13, no. 5, pp. 419-432, 2018e.

Vaidyanathan, S., Akgul, A., Kacar, S., and Cavusoglu, U., A new 4-D chaotic hyperjerk system, its synchronization, circuit design and applications in RNG, image encryption and chaos-based steganography, *European Physical Journal Plus*, vol. 133, no. 2, pp. 46, 2018f.

Voorsluijs, V. and Decker, Y.D., Emergence of chaos in a spatially confined reactive system, *Physica D: Nonlinear Phenomena*, vol. 335, pp. 1-9, 2016.

Wolf, A., Swift, J.B., Swinney, H.L., and Vastano, J.A., Determining Lyapunov exponents from a time series, *Physica D: Nonlinear Phenomena*, vol. 16, no. 3, pp. 285–317, 1985.

Wu, X., Bai, C., and Kan, H., A new color image cryptosystem via hyperchaos synchronization, *Communications in Nonlinear Science and Numerical Simulation*, vol. 19, no. 6, pp. 1884-1897, 2014.

Xue, H.W., Du, J., Li, S.L. and Ma, W.J., Region of interest encryption for color images based on a hyperchaotic system with three positive Lyapunov exponents, *Optics and Laser Technology*, vol. 106, pp. 506-516, 2018.

Biographies

Sundarapandian Vaidyanathan is a Professor and Dean at the Research and Development Centre, Vel Tech University, Chennai, India. He received his D.Sc in Electrical and Systems Engineering from Washington University, St. Louis, USA in 1996. He has published over 460 Scopus-indexed research papers. His current research focuses on control systems, chaos theory, chaotic and hyperchaotic systems, sliding mode control, neuro-fuzzy control, computational science, circuits and memristors. He is the Editor-in-Chief of International Journal of Nonlinear Dynamics and Control (IJNDC), Inderscience Publishers, Olney, UK. He is also in the Editorial Boards of many control journals published by Inderscience, Olney, UK.

Aceng Sambas is currently a Lecturer at the Muhammadiyah University of Tasikmalaya, Indonesia since 2015. He received his MSc in Mathematics from the Universiti Sultan Zainal Abidin (UniSZA), Malaysia in 2015. His current research focuses on dynamical systems, chaotic signals, electrical engineering, computational science, signal processing, robotics, embedded systems and artificial intelligence.

Sukono is a lecturer in the Department of Mathematics, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran. Currently serves as Head of Master's Program in Mathematics, the field of applied mathematics, with a field of concentration of financial mathematics and actuarial sciences.

Subiyanto is a lecturer in the Department of Marine Science, Faculty of Fishery and Marine Science, Universitas Padjadjaran. He received his Ph.D in School of Ocean Engineering from Universiti Malaysia Terengganu (UMT), Malaysia in 2017. His research focuses on applied mathematics, numerical analysis and computational science.

Mustafa Mamat is currently a Professor and the Dean of Graduate School at Universiti Sultan Zainal Abidin (UniSZA), Malaysia since 2013. He was first appointed as a Lecturer at the Universiti Malaysia Terengganu (UMT) in 1999. He obtained his PhD from the UMT in 2007 with specialization in optimization. Later on, he was appointed as a Senior Lecturer in 2008 and then as an Associate Professor in 2010 also at the UMT. To date, he has successfully supervised more than 60 postgraduate students and published more than 200 research papers in various international journals and conferences. His research interests include conjugate gradient methods, steepest descent methods, Broyden's family and quasi-Newton methods.

Abdul Talib Bon is a Professor of Production and Operations Management in the Faculty of Technology Management and Business at the Universiti Tun Hussein Onn Malaysia since 1999. He has a PhD in Computer Science, which he obtained from the Universite de La Rochelle, France in the year 2008. His doctoral thesis was on topic Process Quality Improvement on Beltline Moulding Manufacturing. He studied Business Administration in the Universiti Kebangsaan Malaysia for which he was awarded the MBA in the year 1998. He's bachelor degree and diploma in Mechanical Engineering which his obtained from the Universiti Teknologi Malaysia. He received his postgraduate certificate in Mechatronics and Robotics from Carlisle, United Kingdom in 1997. He had published more 150 International Proceedings and International Journals and 8 books. He is a member of MSORSM, IIF, IEOM, IIE, INFORMS, TAM and MIM.