ADAPTIVE LAG SYNCHRONIZATION OF A MODIFIED RUCKLIDGE CHAOTIC SYSTEM WITH UNKNOWN PARAMETERS AND ITS LABVIEW IMPLEMENTATION

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ABSTRACT*—Chaos theory has wide applications in several branches of science and engineering. The discovery of novel chaotic systems in various applications, their qualitative properties and the control of such systems are active research areas. This paper announces a novel chaotic system obtained by modifying the equations of the Rucklidge chaotic system (1992) for nonlinear double convection. The Lyapunov exponents of the modified Rucklidge chaotic system are obtained as* $L_1 = 0.4283$, $L_2 = 0$ *and* $L_3 = -3.4301$. *Also, the Lyapunov dimension of the modified Rucklidge chaotic system is derived as* $D_L = 2.1249$. *Next, an adaptive feedback controller is defined for the lag synchronization of the identical modified Rucklidge chaotic systems with unknown parameters. Finally, a circuit design of the modified Rucklidge chaotic system and its adaptive lag synchronization are implemented in LabVIEW to validate the results for the theoretical chaotic model.*

Keywords— chaos; chaotic systems; Rucklidge system; delay systems; lag synchronization; circuit design; LabVIEW.

I. INTRODUCTION

A chaotic system is usually characterized by having a dense collection of points with periodic orbits, being sensitive to initial conditions of the system ("butterfly effect") and also being topologically transitive. A chaotic system is also characterized by the existence of a positive Lyapunov exponent.

The first chaotic system was derived by Lorenz [1], when he was studying convection patterns in the weather model. Numerous 3-D chaotic systems have been found in recent decades such as Rössler system [2], ACT system [3], Rucklidge system [4], Chen system [5], Lü system [6], Chen-Lee system [7], Wang system [8], Zhang-Tang system [9], Sundarapandian-Pehlivan system [10], Pehlivan system [11], Vaidyanathan systems [12-28], Thanh system [29-30], etc.

Chaos modelling have applications in many areas such as chemical reactors [31-40], Brusselators [41-43], Dynamo systems [44-48], Tokamak systems [49-50], biology models [51-60], neurology [61-70], ecology models [71-77], memristive devices [78-80], economics [81-82], etc.

Recently, many methods have been developed in the control literature for synchronizing a pair of chaotic systems such as active control [83-100], adaptive control [101-120], backstepping control [121-130], sliding control [131-140], etc.

Due to the presence of signal propagation delays, we cannot always assume that the states in the response system should synchronize with the driving signals at exactly the same time. Thus, in designing a controller for synchronizing chaotic systems, the propagation delays should be taken into consideration. In such a case, the response state $y(t)$ is expected to synchronize with the driving signal with certain transmission lag τ. In other words, the synchronization goal aims to drive the lag synchronization error $e(t) = y(t) - x(t-\tau)$ to zero asymptotically as $t \to \infty$.

Lag synchronization is investigated with many approaches such as intermittent control [141], adaptive control [142], sliding mode control [143], fuzzy logic control [144], etc.

In fluid mechanics modelling, cases of two-dimensional convection in a horizontal layer of Boussinesq fluid with lateral constraints were studied by Rucklidge [4]. When the convection takes place in a fluid layer rotating uniformly about a vertical axis and in the limit of tall thin rolls, convection in an imposed vertical magnetic field and convection in a rotating fluid layer are both modeled by the Rucklidge system of ordinary differential equations, which produces chaotic solutions like the Lorenz system [1].

In this research work, we derive a novel chaotic system by modifying the equations of the Rucklidge chaotic system [4]. We discuss the qualitative properties of the modified Rucklidge chaotic system such as dissipativity, stability of the equilibrium points, Lyapunov exponents and Lyapunov dimension. Next, we derive new results for the lag synchronization of the identical modified Rucklidge chaotic systems via adaptive control method. Finally, we present details of the circuit simulation and LabVIEW implementation of the modified Rucklidge chaotic system and adaptive lag synchronization of the modified Rucklidge chaotic systems.

II. A MODIFIED RUCKLIDGE CHAOTIC SYSTEM

The Rucklidge chaotic system [4] for nonlinear double convection is described by

$$\begin{aligned} \dot{x}_1 &= -ax_1 + bx_2 - x_2 x_3 \\ \dot{x}_2 &= x_1 \\ \dot{x}_3 &= -x_3 + x_2^2 \end{aligned} \tag{1}$$

where x_1, x_2, x_3 are the states and a, b are constant, positive, parameters.

The Rucklidge system (1) is *chaotic* when the parameter values are taken as

$$a = 2, \ \ b = 6.7 \tag{2}$$

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

$$L_1 = 0.1877, \ \ L_2 = 0, \ \ L_3 = -3.1893 \tag{3}$$

Also, the Lyapunov dimension of the Rucklidge chaotic system (1) is derived as

$$D_L = 2 + \frac{L_1 + L_2}{|L_3|} = 2.0589 \quad (4)$$

In this research work, we derive a novel chaotic system by modifying the equations of the Rucklidge chaotic system (1) and we obtain the novel system

$$\begin{aligned} \dot{x}_1 &= -ax_1 + bx_2 - x_2x_3 \\ \dot{x}_2 &= x_1 \\ \dot{x}_3 &= -x_3 + x_2^4 \end{aligned} \quad (5)$$

In this work, we show that the modified Rucklidge system (5) is chaotic when the parameter values are taken as

$$a = 2, \ \ b = 10 \quad (6)$$

For numerical simulations, we take the initial conditions of the modified Rucklidge system (5) as

$$x_1(0) = 1.2, \ \ x_2(0) = 0.8, \ \ x_3(0) = 1.4 \quad (7)$$

The basic qualitative properties of the modified Rucklidge chaotic system (5) are described in Section III.

The Lyapunov exponents of the modified Rucklidge chaotic system (5) are obtained as

$$L_1 = 0.4283, \ \ L_2 = 0, \ \ L_3 = -3.4301 \quad (8)$$

Also, the Lyapunov dimension of the modified Rucklidge chaotic system (5) is derived as

$$D_L = 2 + \frac{L_1 + L_2}{|L_3|} = 2.1249 \quad (9)$$

It is noted that the Maximal Lyapunov Exponent (MLE) of the modified Rucklidge chaotic system (5) is greater than that of the Rucklidge chaotic system (1). It is also noted that the Lyapunov dimension of the modified Rucklidge chaotic system (5) is greater than that of the Rucklidge chaotic system (1). This shows that the modified Rucklidge chaotic system (5) has more chaotic behavior than the Rucklidge chaotic system (1).

Fig. 1 shows the strange chaotic attractor of the modified Rucklidge chaotic system (5).

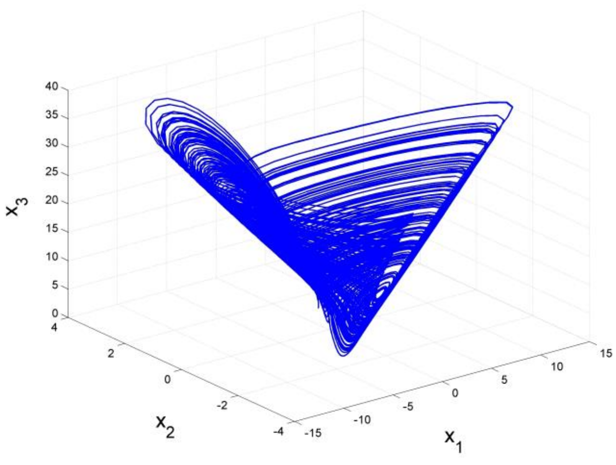

Fig. 1 Strange attractor of the modified Rucklidge chaotic system

The modified Rucklidge chaotic system with delay is given by the 3-D dynamics

$$\begin{aligned} \dot{x}_1(t-\tau) &= -ax_1(t-\tau) + bx_2(t-\tau) - x_2(t-\tau)x_3(t-\tau) \\ \dot{x}_2(t-\tau) &= x_1(t-\tau) \\ \dot{x}_3(t-\tau) &= -x_3(t-\tau) + x_2^4(t-\tau) \end{aligned} \quad (10)$$

where $\tau > 0$ is the time-delay and a, b are constant, positive parameters.

III. ANALYSIS OF THE MODIFIED RUCKLIDGE CHAOTIC SYSTEM

A. *Dissipativity*

In vector notation, the modified Rucklidge system (5) can be expressed as

$$\dot{x} = f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{bmatrix}. \quad (11)$$

The divergence on the vector field f on R^3 is given by

$$\nabla \cdot f = \frac{\partial f_1(x)}{\partial x_1} + \frac{\partial f_2(x)}{\partial x_2} + \frac{\partial f_3(x)}{\partial x_3}. \quad (12)$$

Let Ω be any region in R^3 with a smooth boundary. Let $\Omega(t) = \Phi_t(\Omega)$, where Φ_t is the flow of f. Let $V(t)$ denote the volume of $\Omega(t)$.

By Liouville's theorem, we have

$$\dot{V}(t) = \int_{\Omega(t)} (\nabla \cdot f)\, dx_1 dx_2 dx_3 \quad (13)$$

The divergence of the flow of the system (5) is found as

$$\nabla \cdot f = \frac{\partial f_1}{\partial x_1} + \frac{\partial f_2}{\partial x_2} + \frac{\partial f_3}{\partial x_3} = -(a+1) = -\mu \quad (14)$$

where $\mu = a + 1 = 3 > 0.$

Substituting the value of $\nabla \cdot f$ in (13), we get

$$\dot{V}(t) = \int_{\Omega(t)} (-\mu)\, dx_1 dx_2 dx_3 = -\mu V(t) \quad (15)$$

Integrating the linear differential equation (15), we get

$$V(t) = \exp(-\mu t) V(0) \quad (16)$$

Since $\mu > 0$, it follows from Eq. (16) that $V(t) \to 0$ exponentially as $t \to \infty$. Thus, the modified Rucklidge system (5) is dissipative. Thus, the system limit sets are ultimately confined into a specific limit set of zero volume, and the asymptotic motion of the system (5) settles onto a strange attractor of the system.

B. *Symmetry*

The system (5) is invariant under the coordinates transformation

$$(x_1, x_2, x_3) \mapsto (-x_1, -x_2, x_3) \quad (17)$$

The transformation (17) persists for all values of the system parameters. Thus, the system (5) has rotation symmetry about the $x_3 -$axis and any non-trivial trajectory of the system (5) must have a twin trajectory.

*C. **Invariance***

It is easy to see that the $x_3 -$axis is invariant for the flow of the system (5). Also, the invariant motion of the flow of the system on the $x_3 -$axis is governed by the scalar differential equation

$$\dot{x}_3 = -x_3 \tag{18}$$

which is globally exponentially stable.

D. Lyapunov Exponents and Lyapunov Dimension

We take the parameter values of the modified Rucklidge system (5) as in the chaotic case, i.e.

$$a = 2, \quad b = 10 \tag{19}$$

We take the initial state as

$$x_1(0) = 1.2, \quad x_2(0) = 0.8, \quad x_3(0) = 1.4 \tag{20}$$

The Lyapunov exponents of the modified Rucklidge system (5) are numerically obtained using MATLAB as

$$L_1 = 0.4283, \ L_2 = 0, \ L_3 = -3.4307 \tag{21}$$

Eq. (29) shows that the modified Rucklidge system (5) is a chaotic system since it has a positive Lyapunov exponent, L_1.

Since $L_1 + L_2 + L_3 = -3.0018 < 0,$ it is immediate that the modified Rucklidge chaotic system (5) is dissipative.

The Lyapunov dimension of the modified Rucklidge chaotic system (5) is determined as

$$D_L = 2 + \frac{L_1 + L_2}{|L_3|} = 2.1249, \tag{22}$$

which is fractional.

IV. ADAPTIVE LAG SYNCHRONIZATION OF MODIFIED RUCKLIDGE CHAOTIC SYSTEMS

For the master system defined by the modified Rucklidge chaotic system (10) with unknown parameters a and b, the slave system can be described as

$$\begin{aligned} \dot{y}_1 &= -ay_1 + by_2 - y_2 y_3 + u_1 \\ \dot{y}_2 &= y_1 + u_2 \\ \dot{y}_3 &= -y_3 + y_2^4 + u_3 \end{aligned} \tag{23}$$

where u_1, u_2, u_3 are nonlinear controllers to be designed using estimates $\hat{a}(t), \hat{b}(t)$ of the unknown system parameters so that the systems (10) and (23) can be synchronized.

The lag synchronization error is defined as

$$\begin{aligned} e_1(t) &= y_1(t) - x_1(t-\tau) \\ e_2(t) &= y_2(t) - x_2(t-\tau) \\ e_3(t) &= y_3(t) - x_3(t-\tau) \end{aligned} \tag{24}$$

where $\tau > 0$ is a constant representing time delay or lag.

Then the lag synchronization error dynamics can be easily obtained as

$$\begin{aligned} \dot{e}_1 &= -ae_1 + be_2 - y_2(t) y_3(t) \\ &\quad + x_2(t-\tau) x_3(t-\tau) + u_1 \\ \dot{e}_2 &= e_1 + u_2 \\ \dot{e}_3 &= -e_3 + y_2^4(t) - x_2^4(t-\tau) + u_3 \end{aligned} \tag{25}$$

We consider an adaptive feedback controller defined by

$$\begin{aligned} u_1 &= \hat{a}(t) e_1 - \hat{b}(t) e_2 + y_2(t) y_3(t) \\ &\quad - x_2(t-\tau) x_3(t-\tau) - k_1 e_1 \\ u_2 &= -e_1 - k_2 e_2 \\ u_3 &= e_3 - y_2^4(t) + x_2^4(t-\tau) - k_3 e_3 \end{aligned} \tag{26}$$

where $\hat{a}(t), \hat{b}(t)$ are estimates of the unknown parameters $a, b,$ respectively, and k_1, k_2, k_3 are positive gain constants.

Substituting (26) into (25), we obtain the closed-loop error dynamics as

$$\begin{aligned} \dot{e}_1 &= -[a - \hat{a}(t)] e_1 + [b - \hat{b}(t)] e_2 - k_1 e_1(t) \\ \dot{e}_2 &= -k_2 e_2(t) \\ \dot{e}_3 &= -k_3 e_3(t) \end{aligned} \tag{27}$$

We define the parameter estimation errors as

$$\begin{aligned} e_a(t) &= a - \hat{a}(t) \\ e_b(t) &= b - \hat{b}(t) \end{aligned} \tag{28}$$

Substituting (28) into (27), we get the error dynamics as

$$\begin{aligned} \dot{e}_1 &= -e_a e_1 + e_b e_2 - k_1 e_1(t) \\ \dot{e}_2 &= -k_2 e_2(t) \\ \dot{e}_3 &= -k_3 e_3(t) \end{aligned} \tag{29}$$

Differentiating (28), we obtain

$$\begin{aligned} \dot{e}_a &= -\dot{\hat{a}}(t) \\ \dot{e}_b &= -\dot{\hat{b}}(t) \end{aligned} \tag{30}$$

Next, we consider the Lyapunov function defined by

$$V = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2 + e_a^2 + e_b^2 \right), \tag{31}$$

which is positive definite on R^5.

Differentiating V along the trajectories of (29) and (30), we obtain

$$\begin{aligned} \dot{V} &= -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 + e_a \left[-e_1^2 - \dot{\hat{a}} \right] \\ &\quad + e_b \left[e_1 e_2 - \dot{\hat{b}} \right] \end{aligned} \tag{32}$$

In view of (32), we take the parameter update law as

$$\begin{aligned} \dot{\hat{a}} &= -e_1^2 \\ \dot{\hat{b}} &= e_1 e_2 \end{aligned} \tag{33}$$

Next, we state the main result of this section.

Theorem 1. The time-delayed modified Rucklidge chaotic system (10) and the modified Rucklidge chaotic system (23) with unknown system parameters are globally and exponentially synchronized by the adaptive feedback control law (26) and the parameter update law (33), where k_1, k_2, k_3 are positive gain constants.

Proof. Substituting (33) into (32), we obtain the time-derivative of the quadratic Lyapunov function V as

$$\dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 \tag{34}$$

which is a negative semi-definite function on R^5.

Thus, using Barbalat's lemma [145], we conclude that $e(t) \to 0$ as $t \to \infty$ for all initial conditions $e(0) \in R^3$.

This completes the proof. ■

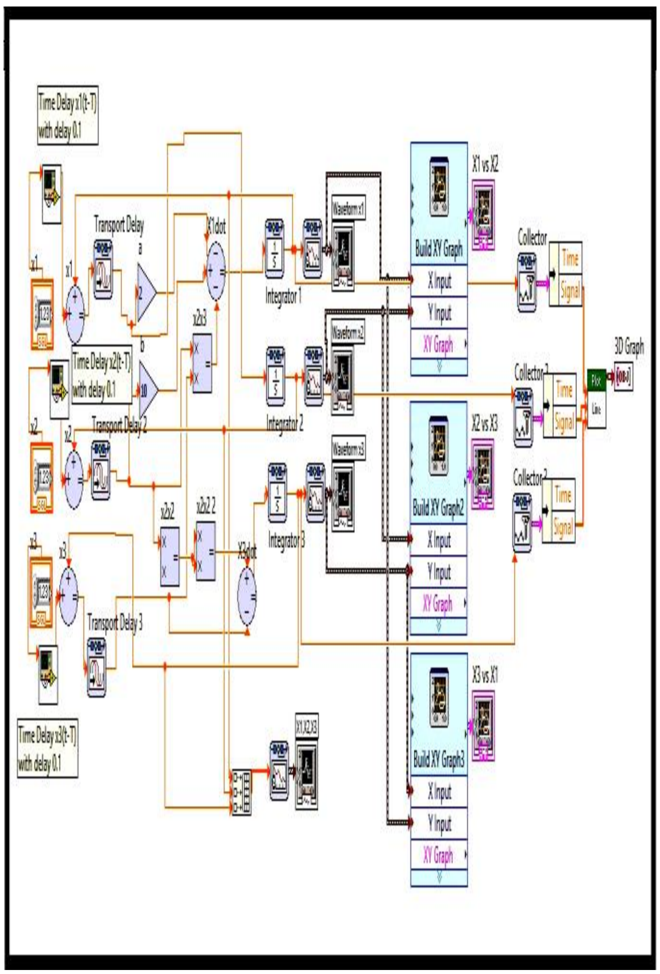

Fig. 2 LabVIEW implementation of the time-delayed modified Rucklidge chaotic system

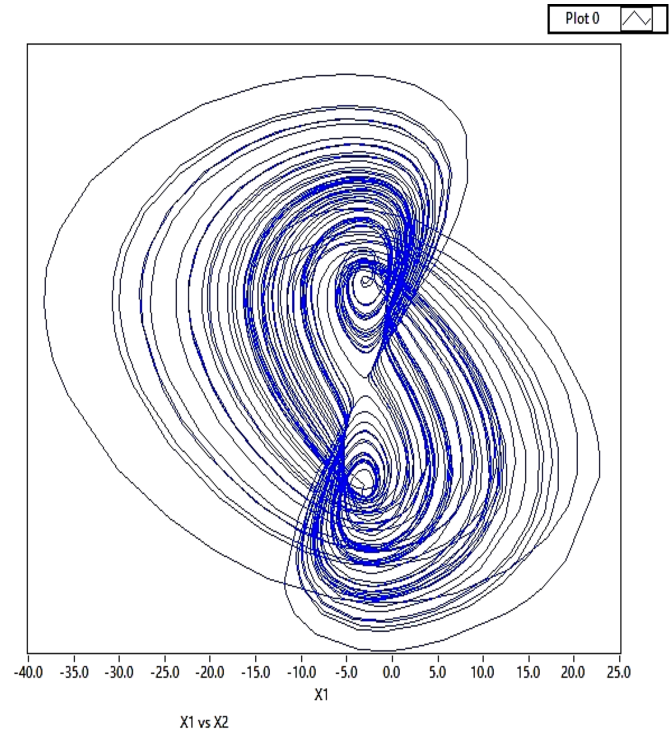

Fig. 3 (x_1, x_2) **–phase portrait of the time-delayed modified Rucklidge chaotic system**

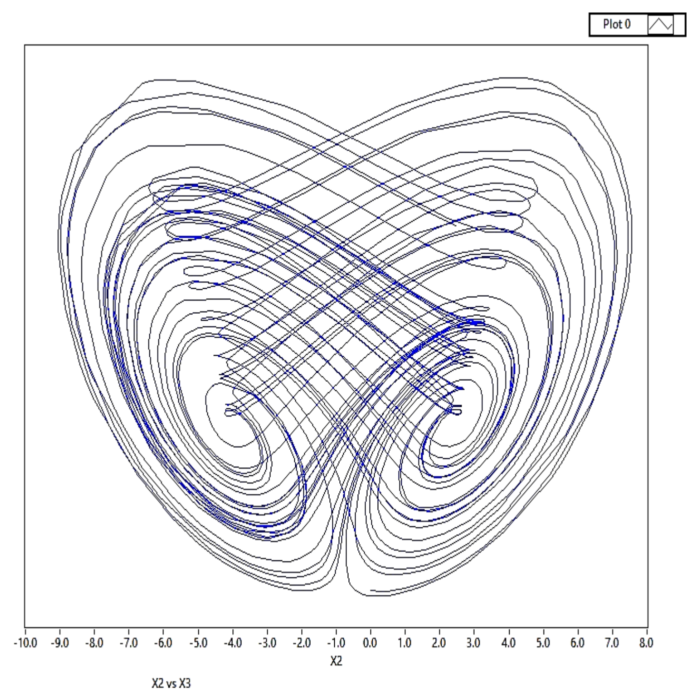

Fig. 4 (x_2, x_3) **–phase portrait of the time-delayed modified Rucklidge chaotic system**

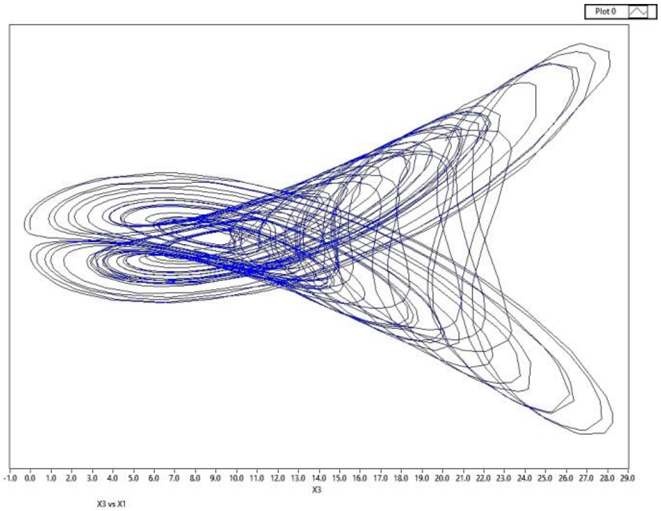

Fig. 5 (x_3, x_1) **-phase portrait of the time-delayed modified Rucklidge chaotic system**

V. LabVIEW Implementation of the Modified Rucklidge Chaotic System

Fig. 2 shows the implementation of the modified Rucklidge chaotic system (10) in LabVIEW using the Control Design and Simulation Loop.

For numerical simulations, we take

$$\tau = 0.1,\ a = 2,\ b = 10 \tag{35}$$

and initial state as

$$x_1(0) = 1.2,\ x_2(0) = 0.8,\ x_3(0) = 1.4. \tag{36}$$

Figures 3-5 show the 2-D phase portraits of the modified Rucklidge chaotic system (10).

VI. LabVIEW Implementation of the Adaptive Lag Synchronization of the Modified Rucklidge Systems

In this section, the adaptive control method for the lag synchronization of the modified Rucklidge chaotic systems discussed in Section III is implemented using LabVIEW.

Fig. 6 shows the design of slave subsystem (23) using LabVIEW. Fig. 7 shows the design in LabVIEW for the adaptive controller u defined by Eq. (26).

For numerical simulations, the initial values of the master system (10) are taken as

$$x_1(0) = 1.4,\ x_2(0) = 1.2,\ x_3(0) = 0.8 \tag{37}$$

The initial values of the slave system (23) are taken as

$$y_1(0) = 0.4,\ y_2(0) = 1.7,\ y_3(0) = 0.5 \tag{38}$$

The initial values of the parameter estimates are taken as

$$\hat{a}(0) = 0.8,\ \hat{b}(0) = 6.3 \tag{39}$$

The time-delay is taken as $\tau = 0.1$.

Fig. 8 shows the time history of the lag synchronization errors.

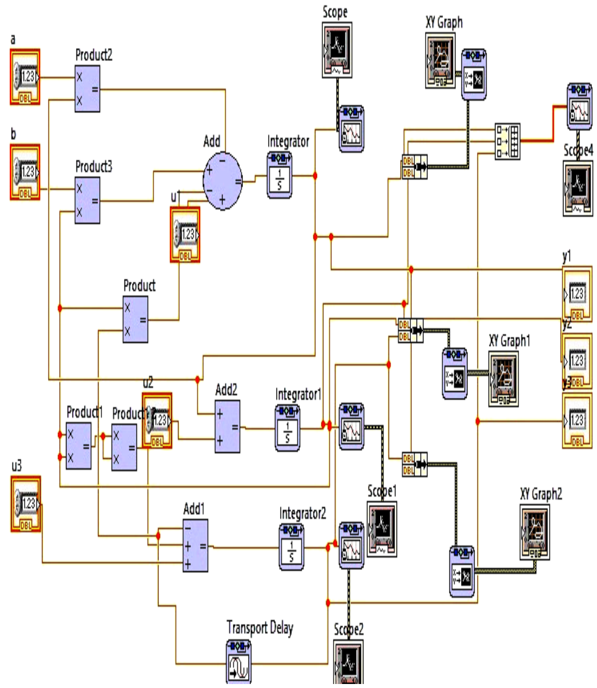

Fig. 6 LabVIEW implementation of the slave system

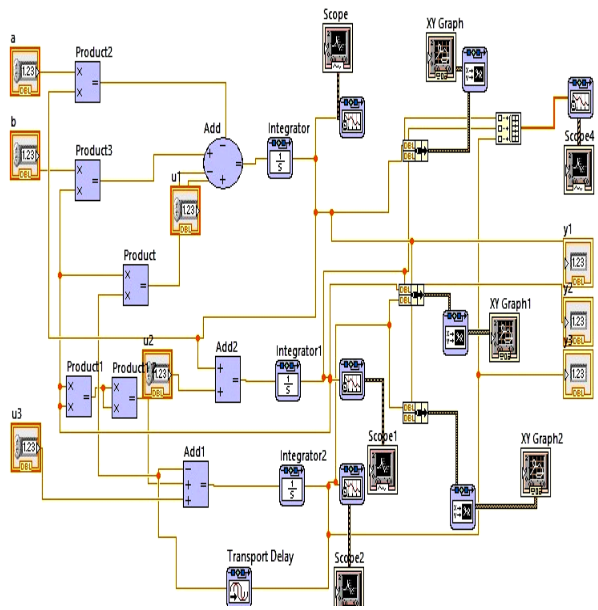

Fig. 7 LabVIEW implementation of the adaptive controller for lag synchronization

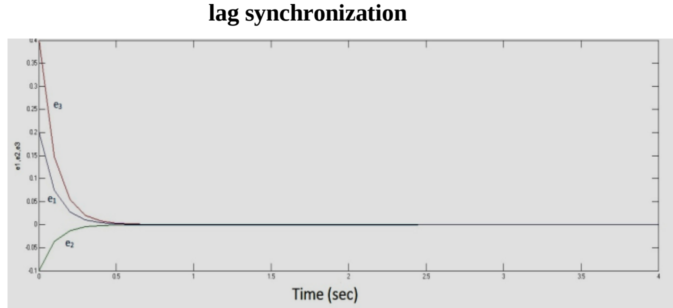

Fig. 8 Time-history of the lag synchronization errors

VII. CONCLUSIONS

In this paper, we have discovered a novel chaotic system, which has been obtained by modifying the equations of the Rucklidge chaotic system (1992) for nonlinear double convection. The qualitative properties of the modified Rucklidge chaotic system have been derived. It is also noted that the modified Rucklidge chaotic system is dissipative. This research work also derived new results for the adaptive lag synchronization of identical modified Rucklidge chaotic systems. To validate the results for the theoretical model, we presented LabVIEW implementation of the modified Rucklidge chaotic system with delay and adaptive controller design for the lag synchronization of the modified Rucklidge chaotic systems.

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