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## 3-Cells Cellular Neural Network (CNN) Attractor and its Adaptive Biological Control

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**Abstract:** Recent research has shown the importance of biological control in many biological systems appearing in nature. In computer science, machine learning and biology, cellular neural networks (CNN) are a parallel computing paradigm, similar to neural networks with the difference that communication is allowed between neighbouring units only. CNN has wide applications and recently, CNN is found to have many applications in biology and applied areas of biology. Chua and Yang introduced the cellular neural network (CNN) in 1988 as a nonlinear dynamical system composed by an array of elementary and locally interacting nonlinear subsystems, which are called cells. In this research work, we discuss the properties of the 3-cells CNN attractor discovered by Arena et al. (1998). We also derive new results for the adaptive biological control of the 3-cells CNN attractor. All the main results are proved using Lyapunov stability theory. Also, numerical simulations have been plotted using MATLAB to illustrate the main results for the 3-cells cellular neural network (CNN) attractor.

**Keywords:** Chaos, chaotic systems, biology, biological control, cellular neural networks, CNN attractor, etc.

### Introduction

Chaos theory describes the qualitative study of deterministic chaotic dynamical systems, and a chaotic system must satisfy 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]. Subsequently, Rössler discovered a 3-D chaotic system in 1976 [4], which is algebraically much simpler than the Lorenz system. These classical systems were followed by the discovery of many 3-D chaotic systems 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 [13-37], Pehlivan system [38], Pham system [39], etc.

Recent research has shown the importance of biological control in many biological systems appearing in nature. In computer science, machine learning and biology, cellular neural networks (CNN) are a parallel computing paradigm, similar to neural networks with the difference that communication is allowed between neighbouring units only. CNN has wide applications and recently, CNN is found to have many applications in biology and applied areas of biology.

In 1988, Chua and Yang introduced the cellular neural network (CNN) as a nonlinear dynamical system composed by an array of elementary and locally interacting nonlinear subsystems, which are called cells [40]. In this research work, we discuss the properties of the 3-cells CNN attractor discovered by Arena et al. [41].

We also derive new results for the adaptive biological control of the 3-cells CNN attractor. All the

main results are proved using Lyapunov stability theory [42]. Also, numerical simulations have been plotted using MATLAB to illustrate the main results for the 3-cells cellular neural network (CNN) attractor.

Active control method is a feedback control strategy which works with the knowledge of system parameters [43-57]. Adaptive control method is a feedback control strategy which is very effective in control theory because it makes use of the estimates of the unknown parameters of the system [58-73]. Chaos theory has many important applications in chemistry [74] and biology [75].

### 3-Cells CNN Attractor

Arena *et al.* (1998, [41]) derived a 3-cells cellular neural network (CNN) attractor, which is described by the 3-D system of differential equations

$$\begin{cases} \dot{x}_1 = -x_1 + \alpha f(x_1) - bf(x_2) - bf(x_3) \\ \dot{x}_2 = -x_2 - bf(x_1) + \beta f(x_2) - af(x_3) \\ \dot{x}_3 = -x_3 - bf(x_1) + af(x_2) + f(x_3) \end{cases} \quad (1)$$

where  $x_1, x_2, x_3$  are the states,  $a, b, \alpha, \beta$  are positive constants and the function  $f(z)$  is defined by

$$f(z) = 0.5 (|z+1| - |z-1|) \text{ where } z \in R \quad (2)$$

In [41], it was shown that the 3-cells CNN system (1) is chaotic when we take the parameter values as

$$\alpha = 1.24, \beta = 1.1, a = 4.4 \text{ and } b = 3.21. \quad (3)$$

For numerical simulations, we take the initial conditions as  $x_1(0) = 0.1, x_2(0) = 0.1$  and  $x_3(0) = 0.1$ .

The 3-D phase portrait of the 3-cells CNN attractor (1) is depicted in Figure 1. The 2-D projections of the 3-cells CNN attractor (1) on the coordinate planes are depicted in Figures 2-4.

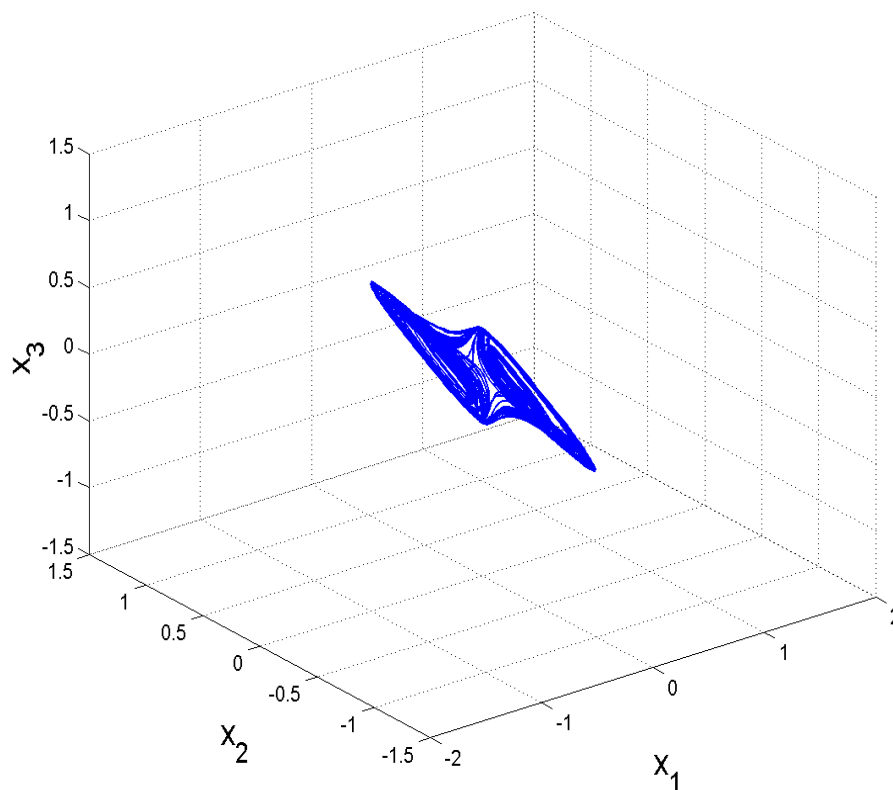
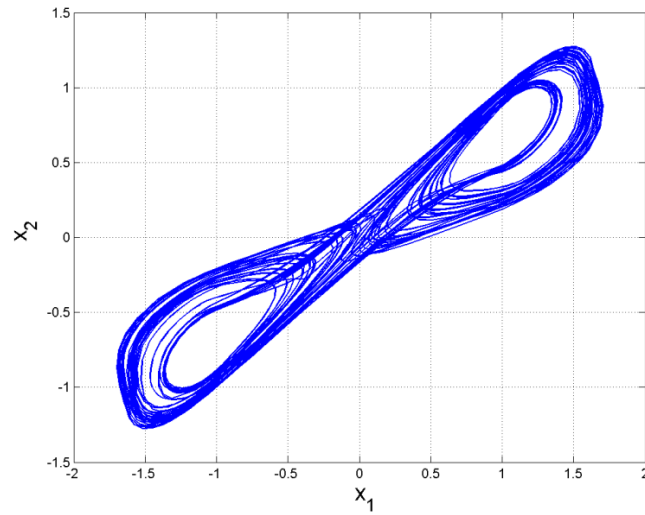
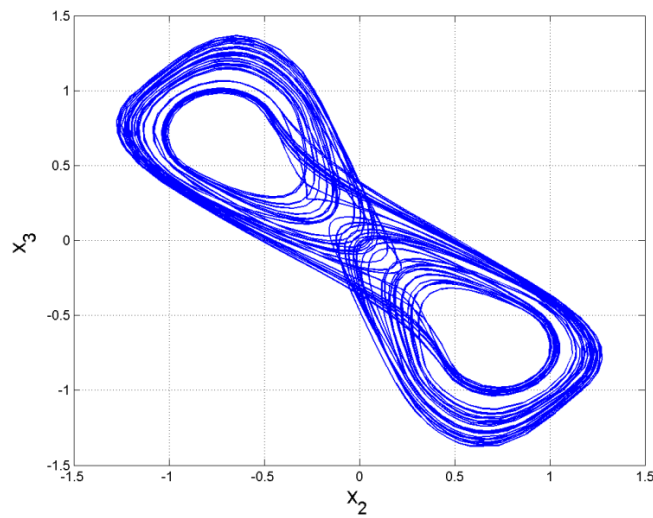


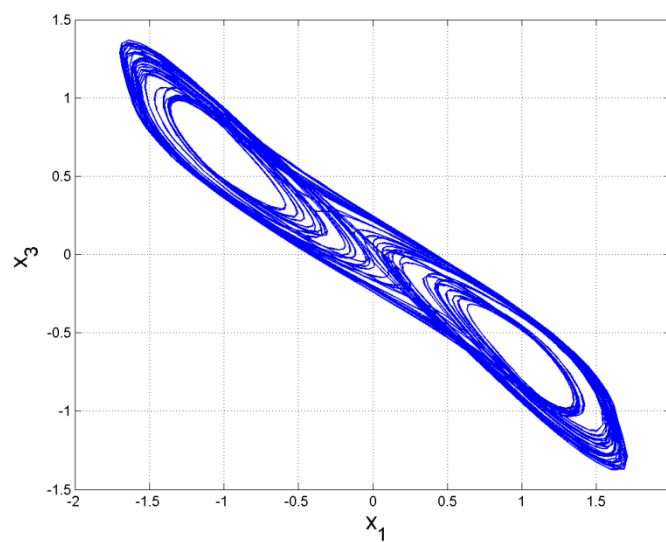
Figure1. The 3-D phase portrait of the 3-cells CNN attractor



**Figure2.**The2-D projection of the 3-cells CNN attractor on  $(x_1, x_2)$  plane



**Figure3.**The2-D projection of the 3-cells CNN attractor on  $(x_2, x_3)$  plane



**Figure4.**The2-D projection of the 3-cells CNN attractor on  $(x_1, x_3)$  plane

### Adaptive Control of the 3-Cells Cellular Neural Network (CNN) Attractor

The chaotic behaviour of the 3-cells cellular neural network (CNN) attractor [41] is a well-known example of a chaotic CNN system. In this section, we consider the controlled 3-cells CNN attractor given by the 3-D dynamics

$$\begin{cases} \dot{x}_1 = -x_1 + \alpha f(x_1) - bf(x_2) - bf(x_3) + u_1 \\ \dot{x}_2 = -x_2 - bf(x_1) + \beta f(x_2) - af(x_3) + u_2 \\ \dot{x}_3 = -x_3 - bf(x_1) + af(x_2) + f(x_3) + u_3 \end{cases} \quad (4)$$

In (4),  $x_1, x_2, x_3$  are the states and  $u_1, u_2, u_3$  are the adaptive controls to be found using estimates of the unknown parameters  $\alpha, \beta, a, b$  of the system. Also, the function  $f(z), z \in R$  is defined by the equation (2).

We consider the adaptive controller defined by

$$\begin{cases} u_1 = x_1 - \hat{\alpha}(t)f(x_1) + \hat{b}(t)f(x_2) + \hat{b}(t)f(x_3) - k_1x_1 \\ u_2 = x_2 + \hat{b}(t)f(x_1) - \hat{\beta}(t)f(x_2) + \hat{a}(t)f(x_3) - k_2x_2 \\ u_3 = x_3 + \hat{b}(t)f(x_1) - \hat{a}(t)f(x_2) - f(x_3) - k_3x_3 \end{cases} \quad (5)$$

where  $k_1, k_2, k_3$  are positive gain constants.

Substituting (5) into (4), we get the closed-loop control system given by

$$\begin{cases} \dot{x}_1 = [\alpha - \hat{\alpha}(t)]f(x_1) - [b - \hat{b}(t)]f(x_2) - [b - \hat{b}(t)]f(x_3) - k_1x_1 \\ \dot{x}_2 = -[b - \hat{b}(t)]f(x_1) + [\beta - \hat{\beta}(t)]f(x_2) - [a - \hat{a}(t)]f(x_3) - k_2x_2 \\ \dot{x}_3 = -[b - \hat{b}(t)]f(x_1) + [a - \hat{a}(t)]f(x_2) - k_3x_3 \end{cases} \quad (6)$$

We define parameter estimation errors as follows:

$$\begin{cases} e_\alpha &= \alpha - \hat{\alpha}(t) \\ e_\beta &= \beta - \hat{\beta}(t) \\ e_a &= a - \hat{a}(t) \\ e_b &= b - \hat{b}(t) \end{cases} \quad (7)$$

Using (7), we can simplify the closed-loopplant dynamics (6) as follows.

$$\begin{cases} \dot{x}_1 = e_\alpha f(x_1) - e_b f(x_2) - e_b f(x_3) - k_1x_1 \\ \dot{x}_2 = -e_b f(x_1) + e_\beta f(x_2) - e_a f(x_3) - k_2x_2 \\ \dot{x}_3 = -e_b f(x_1) + e_a f(x_2) - k_3x_3 \end{cases} \quad (8)$$

Differentiating the parameter estimation errors (8) with respect to time, we get

$$\begin{cases} \dot{e}_\alpha &= -\dot{\hat{\alpha}}(t) \\ \dot{e}_\beta &= -\dot{\hat{\beta}}(t) \\ \dot{e}_a &= -\dot{\hat{a}}(t) \\ \dot{e}_b &= -\dot{\hat{b}}(t) \end{cases} \quad (9)$$

Next, we consider the candidate Lyapunov function given by

$$V(x_1, x_2, x_3, e_\alpha, e_\beta, e_a, e_b) = \frac{1}{2}(x_1^2 + x_2^2 + x_3^2 + e_\alpha^2 + e_\beta^2 + e_a^2 + e_b^2), \quad (10)$$

which is a positive definite function on  $R^7$ .

Differentiating  $v$  along the trajectories of (8) and (9), we obtain

$$\begin{aligned}\dot{V} = & -k_1x_1^2 - k_2x_2^2 - k_3x_3^2 + e_\alpha \left[ x_1f(x_1) - \dot{\hat{\alpha}} \right] + e_\beta \left[ x_2f(x_2) - \dot{\hat{\beta}} \right] \\ & + e_a \left[ -x_2f(x_3) + x_3f(x_2) - \dot{\hat{a}} \right] + e_b \left[ -x_1[f(x_2) + f(x_3)] - (x_2 + x_3)f(x_1) - \dot{\hat{b}} \right]\end{aligned}\quad (11)$$

In view of (11), we take the parameter estimates as follows:

$$\begin{cases} \dot{\hat{\alpha}} = x_1f(x_1) \\ \dot{\hat{\beta}} = x_2f(x_2) \\ \dot{\hat{a}} = -x_2f(x_3) + x_3f(x_2) \\ \dot{\hat{b}} = -x_1[f(x_2) + f(x_3)] - (x_2 + x_3)f(x_1) \end{cases}\quad (12)$$

**Theorem 1.** *The 3-cells CNN chaotic attractor (4) is exponentially stabilized by the adaptive control law (5) and the parameter update law (12), where  $k_1, k_2, k_3$  are positive gain constants.*

**Proof.** The quadratic Lyapunov function  $v$  defined by Eq. (10) is a positive definite function on  $R^7$ .

Substituting the parameter update law (12) into (11), the time-derivative of  $v$  is obtained as

$$\dot{V} = -k_1e_1^2 - k_2e_2^2 - k_3e_3^2, \quad (13)$$

which is a negative semi-definite function on  $R^7$ .

Thus, by Lyapunov stability theory [42], we conclude that the controlled state vector  $x(t) \rightarrow 0$  exponentially as  $t \rightarrow \infty$  for all initial conditions  $x(0) \in R^3$ .

Hence, the 3-cells CNN chaotic attractor (4) is exponentially stabilized by the adaptive control law (5) and the parameter update law (12).

This completes the proof. ■

## 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 (4) and (12).

We take the gain constants as

$$k_1 = 8, \quad k_2 = 8, \quad k_3 = 8$$

The parameter values of the 3-cells CNN chaotic attractor (4) are taken as in the chaotic case, viz.

$$\alpha = 1.24, \quad \beta = 1.1, \quad a = 4.4, \quad b = 3.21.$$

We take the initial conditions of the 3-cells CNN chaotic attractor(4) as

$$x_1(0) = 9.4, \quad x_2(0) = 5.3, \quad x_3(0) = 7.2$$

Also, we take the initial conditions of the parameter estimates as

$$\hat{\alpha}(0) = 5.4, \quad \hat{\beta}(0) = 3.1, \quad \hat{a}(0) = 12.5, \quad \hat{b}(0) = 17.2$$

Figure 5 shows the time-history of the exponential convergence of the states  $x_1, x_2, x_3$  to zero.

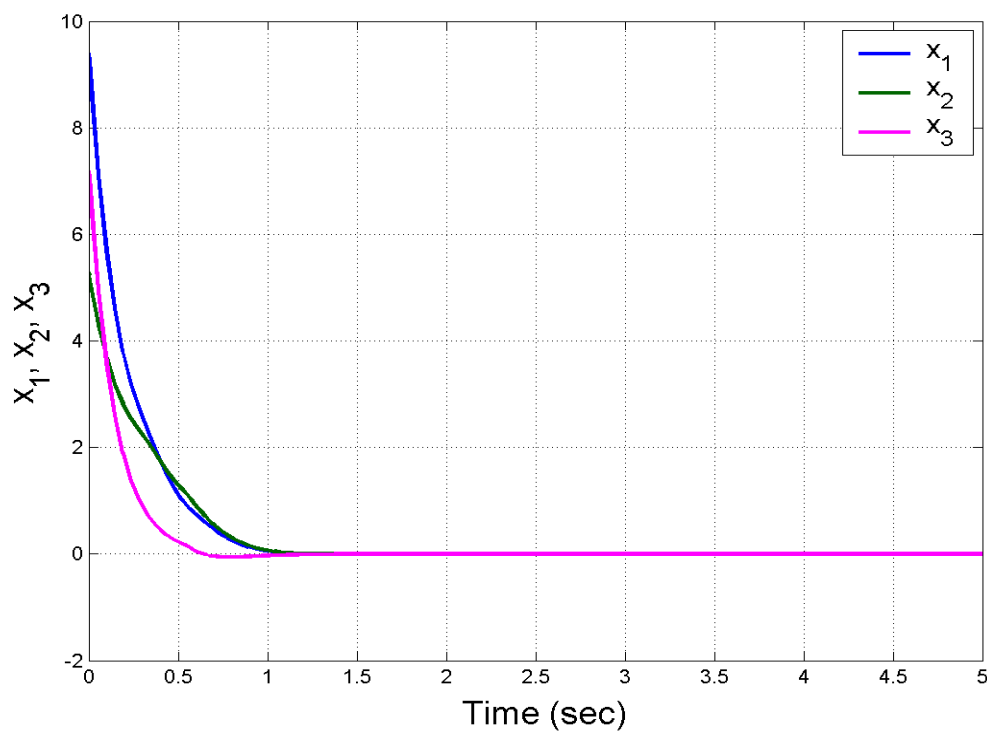


Figure 5. Time-history of the controlled states  $x_1, x_2, x_3$

## Conclusions

In this paper, new results have been derived for the analysis and adaptive control of the 3-cells cellular neural network (CNN) chaotic attractor obtained by Arena *et al.* (1998). After a description and phase portrait of the 3-cells CNN chaotic attractor, we have designed an adaptive feedback controller for the global exponential stabilization of the states of the 3-cells CNN chaotic attractor. The main results have been proved using Lyapunov stability theory and numerical simulations have been illustrated using MATLAB.

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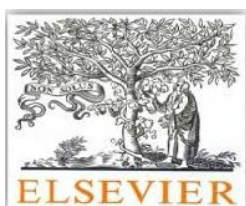
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