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# Synchronization of 3-Cells Cellular Neural Network (CNN) Attractors via Adaptive Control Method

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**Abstract:** In this research work, we first discuss the properties of the 3-cells CNN attractor discovered by Arena et al. (1998). 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. We also derive new results for the adaptive biological synchronization of the identical 3-cells CNN attractors. 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, cellular neural networks, CNN attractor, synchronization, 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 classical chaotic systems are due to Lorenz, who discovered chaos while studying a 3-D weather model in 1963 [3], and Rossler, who discovered chaos, while he was studying chemical reactions in 1976 [4]. 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 first analyze the properties of the 3-cells CNN attractor discovered by Arena et al. [41].

We also derive new results for the adaptive biological synchronization of the identical 3-cells CNN attractors. 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

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

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

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

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 and $b = 3.21$. (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 2-3.

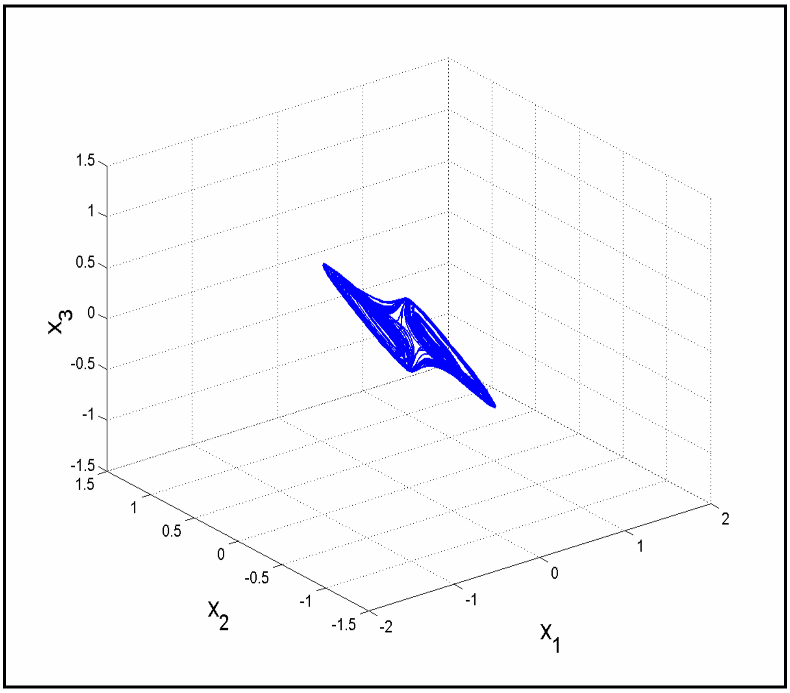


**Figure 1. The 3-D phase portrait of the 3-cells CNN attractor**

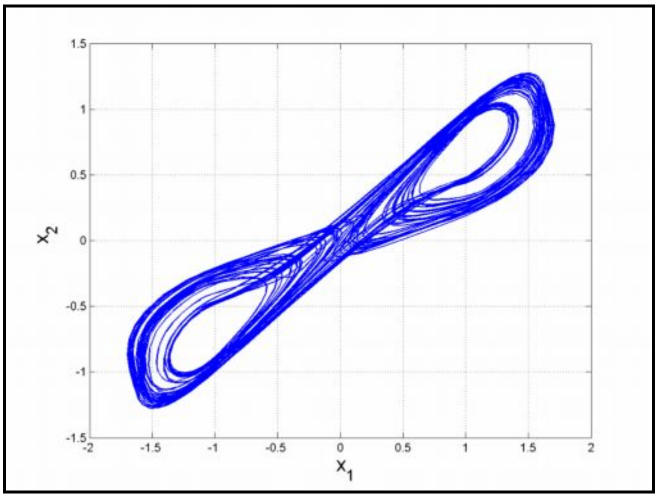


**Figure 2. The 2-D projection of the 3-cells CNN attractor on $(x_1, x_2)$ plane**

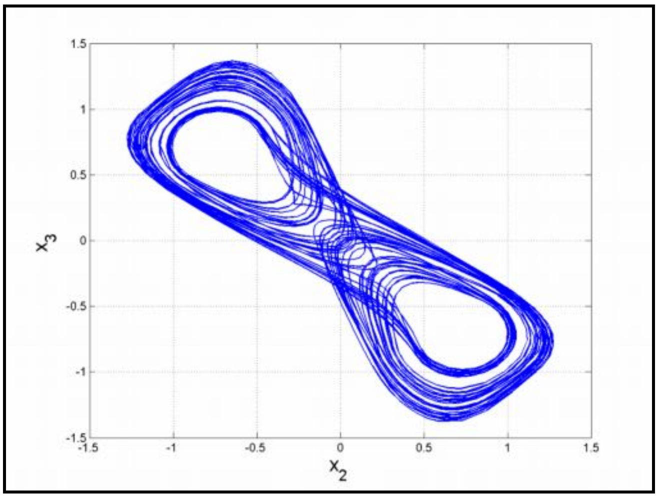


**Figure 3. The 2-D projection of the 3-cells CNN attractor on $(x_2, x_3)$ plane**

**Adaptive Synchronization of the 3-Cells Cellular Neural Network (CNN) Attractors**

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 synchronization of the identical 3-cells CNN attractors.

As the master system, we consider the 3-cells CNN attractor given by the 3-D dynamics

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

In (4), $x_1, x_2, x_3$ are the states and $\alpha, \beta, a, b$ are unknown system parameters. Also, the function $f(z), z \in R$ is defined by the equation (2).

As the slave system, we consider the 3-cells CNN attractor given by the 3-D dynamics

$$\begin{cases} \dot{y}_1 = -y_1 + \alpha f(y_1) - bf(y_2) - bf(y_3) + u_1 \\ \dot{y}_2 = -y_2 - bf(y_1) + \beta f(y_2) - af(y_3) + u_2 \\ \dot{y}_3 = -y_3 - bf(y_1) + af(y_2) + f(y_3) + u_3 \end{cases} \tag{5}$$

In (5), $y_1, y_2, y_3$ are the states and $u_1, u_2, u_3$ are adaptive controls to be determined.

To simplify the notation, we define a new function $G(u,v)$ as follows:

$$G(u,v) = f(v) - f(u), \text{ where } u, v \in R. \tag{6}$$

We define the synchronization error between the systems (4) and (5) as

$$\begin{cases} e_1 = y_1 - x_1 \\ e_2 = y_2 - x_2 \\ e_3 = y_3 - x_3 \end{cases} \tag{7}$$

Using (4), (5) and (6), the synchronization error dynamics is obtained as follows:

$$\begin{cases} \dot{e}_1 = -e_1 + \alpha G(x_1, y_1) - bG(x_2, y_2) - bG(x_3, y_3) + u_1 \\ \dot{e}_2 = -e_2 - bG(x_1, y_1) + \beta G(x_2, y_2) - aG(x_3, y_3) + u_2 \\ \dot{e}_3 = -e_3 - bG(x_1, y_1) + aG(x_2, y_2) + G(x_3, y_3) + u_3 \end{cases} \tag{8}$$

We consider the adaptive controller defined by

$$\begin{cases} u_1 = e_1 - \hat{\alpha}(t)G(x_1, y_1) + \hat{b}(t)G(x_2, y_2) + \hat{b}(t)G(x_3, y_3) - k_1 e_1 \\ u_2 = e_2 + \hat{b}(t)G(x_1, y_1) - \hat{\beta}(t)G(x_2, y_2) + \hat{a}(t)G(x_3, y_3) - k_2 e_2 \\ u_3 = e_3 + \hat{b}(t)G(x_1, y_1) - \hat{a}(t)G(x_2, y_2) - G(x_3, y_3) - k_3 e_3 \end{cases} \tag{9}$$

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

Substituting (9) into (8), we get the closed-loop error dynamics given by

$$\begin{cases} \dot{e}_1 = \left[\alpha - \hat{\alpha}(t)\right]G(x_1, y_1) - \left[b - \hat{b}(t)\right]G(x_2, y_2) - \left[b - \hat{b}(t)\right]G(x_3, y_3) - k_1 e_1 \\ \dot{e}_2 = -\left[b - \hat{b}(t)\right]G(x_1, y_1) + \left[\beta - \hat{\beta}(t)\right]G(x_2, y_2) - \left[a - \hat{a}(t)\right]G(x_3, y_3) - k_2 e_2 \\ \dot{e}_3 = -\left[b - \hat{b}(t)\right]G(x_1, y_1) + \left[a - \hat{a}(t)\right]G(x_2, y_2) - k_3 e_3 \end{cases} \tag{10}$$

We define parameter estimation errors as follows:

$$\begin{cases} e_\alpha = \alpha - \hat{\alpha}(t) \\ e_\beta = \beta - \hat{\beta}(t) \\ e_a = a - \hat{a}(t) \\ e_b = b - \hat{b}(t) \end{cases} \tag{11}$$

Using (11), we can simplify the closed-loop plant dynamics (6) as follows.

$$\begin{cases} \dot{e}_1 = e_\alpha G(x_1, y_1) - e_b G(x_2, y_2) - e_b G(x_3, y_3) - k_1 e_1 \\ \dot{e}_2 = -e_b G(x_1, y_1) + e_\beta G(x_2, y_2) - e_a G(x_3, y_3) - k_2 e_2 \\ \dot{e}_3 = -e_b G(x_1, y_1) + e_a G(x_2, y_2) - k_3 e_3 \end{cases} \tag{12}$$

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

$$\begin{cases} \dot{e}_\alpha = -\dot{\hat{\alpha}} \\ \dot{e}_\beta = -\dot{\hat{\beta}} \\ \dot{e}_a = -\dot{\hat{a}} \\ \dot{e}_b = -\dot{\hat{b}} \end{cases} \tag{13}$$

Next, we consider the candidate Lyapunov function given by

$$V(e_1, e_2, e_3, e_\alpha, e_\beta, e_a, e_b) = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2 + e_\alpha^2 + e_\beta^2 + e_a^2 + e_b^2\right) \tag{14}$$

Differentiating $V$ along the trajectories of (12) and (13), we obtain

$$\dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 + e_\alpha \left[ e_1 G(x_1, y_1) - \dot{\hat{\alpha}} \right] + e_\beta \left[ e_2 G(x_2, y_2) - \dot{\hat{\beta}} \right]$$
$$+ e_a \left[ -e_2 G(x_3, y_3) + e_3 G(x_2, y_2) - \dot{\hat{a}} \right] \quad (15)$$
$$+ e_b \left[ -e_1 \left[ G(x_2, y_2) + G(x_3, y_3) \right] - (e_2 + e_3) G(x_1, y_1) - \dot{\hat{b}} \right]$$

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

$$\begin{cases} \dot{\hat{\alpha}} = e_1 G(x_1, y_1) \\ \dot{\hat{\beta}} = e_2 G(x_2, y_2) \\ \dot{\hat{a}} = -e_2 G(x_3, y_3) + e_3 G(x_2, y_2) \\ \dot{\hat{b}} = -e_1 \left[ G(x_2, y_2) + G(x_3, y_3) \right] - (e_2 + e_3) G(x_1, y_1) \end{cases} \quad (16)$$

**Theorem 1.** *The 3-cells CNN chaotic attractors (4) and (5) are globally and exponentially synchronized by the adaptive control law (9) and the parameter update law (16), where* $k_1, k_2, k_3$ *are positive gain constants.*

**Proof.** The quadratic Lyapunov function $V$ defined by Eq. (14) is a positive definite function on $R^7$.

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

$$\dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2, \quad (17)$$

which is a negative semi-definite function on $R^7$. Thus, by Lyapunov stability theory [42], we conclude that the error vector $e(t) \to 0$ exponentially as $t \to \infty$ for all initial conditions $e(0) \in R^3$.

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 $k_i = 10$ for $i = 1, 2, 3$.

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

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

We take the initial conditions of the master system (4) as

$x_1(0) = 3.4$, $x_2(0) = 2.1$, $x_3(0) = 7.8$

We take the initial conditions of the slave system (5) as

$y_1(0) = 9.2$, $y_2(0) = 6.3$, $y_3(0) = 3.4$

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

$\hat{\alpha}(0) = 2.4$, $\hat{\beta}(0) = 3.1$, $\hat{a}(0) = 7.5$, $\hat{b}(0) = 12.3$

Figures 4-6 show the synchronization of the 3-cells CNN chaotic attractors (4) and (5). Figure 7 shows the time-history of the synchronization errors $e_1, e_2, e_3$.

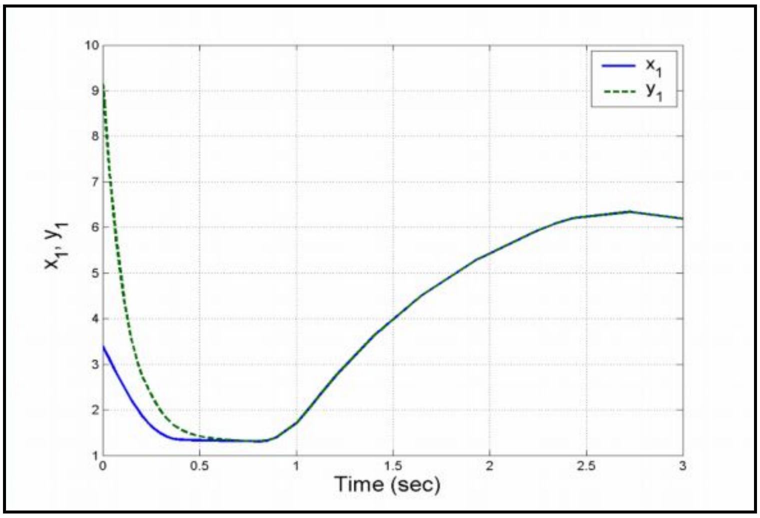


**Figure 4. Synchronization of the states $x_1$ and $y_1$**

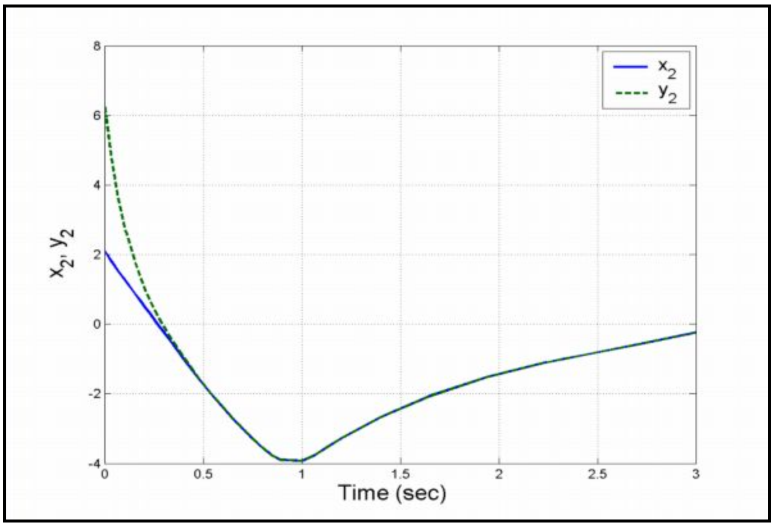


**Figure 5. Synchronization of the states $x_2$ and $y_2$**

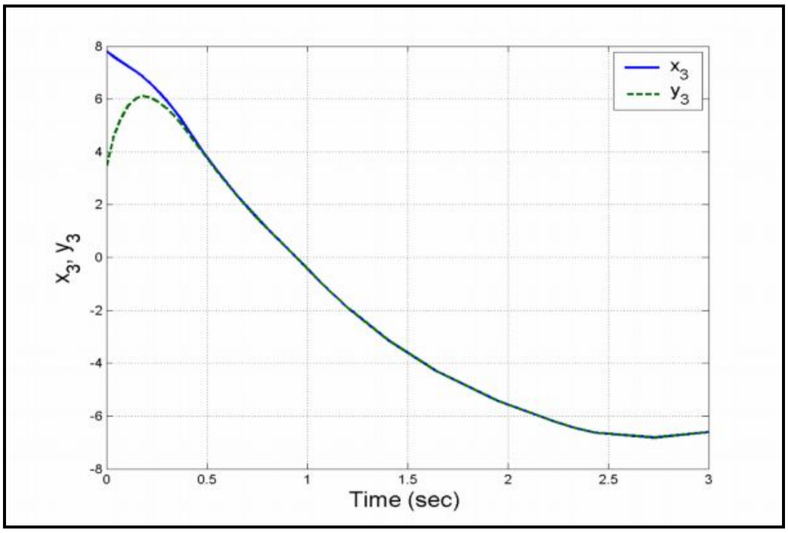


**Figure 6. Synchronization of the states $x_3$ and $y_3$**

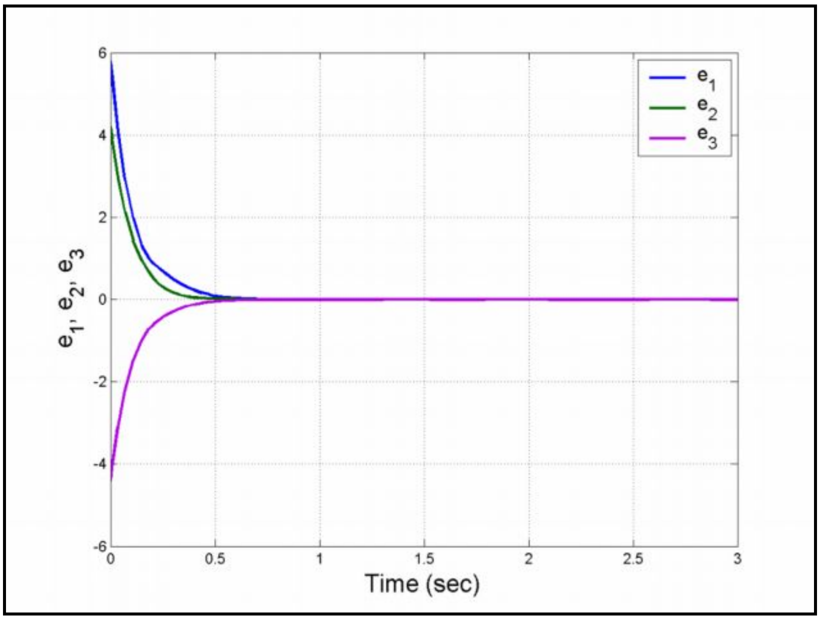


**Figure 7. Time-history of the synchronization errors** $e_1, e_2, e_3$

## Conclusions

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

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