ADAPTIVE CONTROLLER DESIGN FOR THE SYNCHRONIZATION OF MOORE-SPIEGEL AND ACT SYSTEMS WITH UNKNOWN PARAMETERS

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ABSTRACT

In this paper, we design adaptive controllers for the global chaos synchronization of identical Moore-Spiegel systems (1966), identical ACT systems (1981) and non-identical Moore-Spiegel and ACT chaotic systems with unknown parameters. Our adaptive synchronization results derived in this paper for uncertain Moore-Spiegel and ACT systems are established using Lyapunov stability theory. Since the Lyapunov exponents are not required for these calculations, the adaptive control method is very effective and convenient to synchronize identical and non-identical uncertain Moore-Spiegel and ACT chaotic systems. Numerical simulations are shown to demonstrate the effectiveness of the proposed adaptive synchronization schemes for the global chaos synchronization of the uncertain chaotic systems derived in this paper.

KEYWORDS

Adaptive Control, Chaos Synchronization, Nonlinear Control, Moore-Spiegel System, ACT System.

1. INTRODUCTION

Chaotic systems are dynamical systems that are highly sensitive to initial conditions. The sensitive nature of chaotic systems is commonly called as the butterfly effect [1]. Synchronization of chaotic systems is a phenomenon that may occur when two or more chaotic oscillators are coupled or when a chaotic oscillator drives another chaotic oscillator. Because of the butterfly effect, which causes the exponential divergence of the trajectories of two identical chaotic systems started with nearly the same initial conditions, synchronizing two chaotic systems is seemingly a very challenging problem in the chaos literature.

In most of the chaos synchronization approaches, the master-slave or drive-response formalism has been used. If a particular chaotic system is called the master or drive system and another chaotic system is called the slave or response system, then the idea of synchronization is to use the output of the master system to control the slave system so that the output of the slave system tracks the output of the master system asymptotically.

In 1990, Pecora and Carroll [2] introduced a method to synchronize two identical chaotic systems and showed that it was possible for some chaotic systems to be fully synchronized. From then on, chaos synchronization has been widely explored in several fields such as physical systems [3], chemical systems [4], ecological systems [5], secure communications [6-7], etc.

Since the seminal work by Pecora and Carroll (1990), a variety of impressive approaches have been proposed for the synchronization of chaotic systems such as the active control method [8-10], sampled-data feedback synchronization method [11], OGY method [12], time-delay feedback method [13], backstepping method [14], adaptive control method [15-16], sliding mode control method [17], etc.
In this paper, we use adaptive control method for the global chaos synchronization of identical Moore-Spiegel systems (Moore and Spiegel, [18], 1966), identical ACT system (Arneodo, Coullet and Tresser, [19], 1981) and non-identical Moore-Spiegel and ACT systems.

In adaptive synchronization of uncertain chaotic systems, the parameters of the master and slave systems are unknown and we use estimates of the system parameters in devising the state feedback control laws. The adaptive synchronization results derived in this paper are established using Lyapunov stability theory [20].

This paper is organized as follows. In Section 2, we derive results for the adaptive synchronization of identical Moore-Spiegel systems (1966). In Section 3, we derive results for the adaptive synchronization of identical ACT systems (1981). In Section 4, we derive results for the adaptive synchronization of non-identical Moore-Spiegel and ACT chaotic systems. In Section 5, we summarize the main results obtained in this paper.

2. ADAPTIVE SYNCHRONIZATION OF IDENTICAL MOORE-SPIEGEL SYSTEMS

2.1 Theoretical Results

In this section, we discuss the adaptive synchronization of identical Moore-Spiegel systems (Moore and Spiegel, [18], 1966) with unknown parameters.

As the master system, we consider the Moore-Spiegel dynamics described by

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= -x_3 - (\beta - \alpha + \alpha x^2_1) x_2 - \beta \dot{x}_1
\end{align*}
\]

where \(x_1, x_2, x_3\) are the states and \(\alpha, \beta\) are unknown system parameters.

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

\[\alpha = 6 \quad \text{and} \quad \beta = 20.\]

As the slave system, we consider the controlled Moore-Spiegel dynamics described by

\[
\begin{align*}
\dot{y}_1 &= y_2 + u_1 \\
\dot{y}_2 &= y_3 + u_2 \\
\dot{y}_3 &= -y_3 - (\beta - \alpha + \alpha y^2_1) y_2 - \beta y_1 + u_3
\end{align*}
\]

where \(y_1, y_2, y_3\) are the states and \(u_1, u_2, u_3\) are the nonlinear controllers to be designed.

The synchronization error is defined by

\[e_i = y_i - x_i, \quad (i = 1, 2, 3)\]

The strange attractor of the Moore-Spiegel chaotic system (1) is shown in Figure 1.
The error dynamics is easily obtained as

\[
\begin{align*}
\dot{e}_1 &= e_2 + u_1 \\
\dot{e}_2 &= e_3 + u_2 \\
\dot{e}_3 &= -\beta e_1 - (\beta - \alpha)e_2 - e_3 - \alpha(y_1^2 y_2 - x_1^2 x_2) + u_3
\end{align*}
\] (4)

Let us now define the adaptive control functions \( u_1(t), u_2(t), u_3(t) \) as

\[
\begin{align*}
u_1 &= -e_2 - k_1 e_1 \\
u_2 &= -e_3 - k_2 e_2 \\
u_3 &= \hat{\beta} e_1 + (\hat{\beta} - \hat{\alpha}) e_2 + e_3 + \hat{\alpha}(y_1^2 y_2 - x_1^2 x_2) - k_3 e_3
\end{align*}
\] (5)

where \( \hat{\alpha} \) and \( \hat{\beta} \) are estimates of the parameters \( \alpha \) and \( \beta \) respectively, and \( k_i, (i = 1, 2, 3) \) are positive constants.

Substituting the control law (5) into (4), we obtain the error dynamics as

\[
\begin{align*}
\dot{e}_1 &= -k_1 e_1 \\
\dot{e}_2 &= -k_2 e_2 \\
\dot{e}_3 &= -(\beta - \hat{\beta}) (e_1 + e_2) + (\alpha - \hat{\alpha}) (e_2 - y_1^2 y_2 + x_1^2 x_2) - k_3 e_3
\end{align*}
\] (6)

Let us now define the parameter errors as

\[
e_{\alpha} = \alpha - \hat{\alpha} \quad \text{and} \quad e_{\beta} = \beta - \hat{\beta}
\] (7)
Substituting (7) into (6), the error dynamics simplifies to

\[
\begin{align*}
\dot{e}_1 &= -k_1 e_1 \\
\dot{e}_2 &= -k_2 e_2 \\
\dot{e}_3 &= -e_\beta (e_1 + e_2) + e_\alpha (e_2 - y_1^2 y_2 + x_1^2 x_2) - k_3 e_3
\end{align*}
\]  

(8)

For the derivation of the update law for adjusting the estimates of the parameters, the Lyapunov approach is used.

Consider the quadratic Lyapunov function

\[
V = \frac{1}{2} \left( e_1^2 + e_2^2 + e_3^2 + e_\alpha^2 + e_\beta^2 \right)
\]  

(9)

Note also that

\[
\dot{e}_\alpha = -\dot{\alpha} \quad \text{and} \quad \dot{e}_\beta = -\dot{\beta}
\]  

(10)

Differentiating \( V \) along the trajectories of (9) and using (10), we obtain

\[
\dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 + e_\alpha \left[ e_\alpha (e_2 - y_1^2 y_2 + x_1^2 x_2) - \dot{\alpha} \right] + e_\beta \left[ -e_\beta (e_1 + e_2) - \dot{\beta} \right]
\]  

(11)

In view of Eq. (11), the estimated parameters are updated by the following law:

\[
\begin{align*}
\dot{\alpha} &= e_3 (e_2 - y_1^2 y_2 + x_1^2 x_2) + k_4 e_\alpha \\
\dot{\beta} &= -e_3 (e_1 + e_2) + k_5 e_\beta
\end{align*}
\]  

(12)

where \( k_4, k_5 \) are positive constants.

Substituting (12) into (11), we get

\[
\dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 - k_4 e_\alpha^2 - k_5 e_\beta^2
\]  

(13)

which is a negative definite function on \( \mathbb{R}^3 \).

Thus, by Lyapunov stability theory [20], it is immediate that the synchronization error and the parameter error decay to zero exponentially with time for all initial conditions.

Hence, we have proved the following result.

**Theorem 1.** The identical Moore-Spiegel systems (1) and (2) with unknown parameters are globally and exponentially synchronized for all initial conditions by the adaptive control law (5), where the update law for parameters is given by (12) and \( k_i, (i = 1, \ldots, 5) \) are positive constants.
2.2 Numerical Results

For the numerical simulations, the fourth order Runge-Kutta method is used to solve the two systems of differential equations (1) and (2) with the adaptive control law (5) and the parameter update law (12).

For the adaptive synchronization of the Moore-Spiegel systems with parameter values $\alpha = 6, \beta = 20$, we apply the adaptive control law (5) and the parameter update law (12). We take the positive constants $k_i, (i = 1, \ldots, 5)$ as $k_i = 2$ for $i = 1, 2, \ldots, 5$.

Suppose that the initial values of the estimated parameters are $\hat{\alpha}(0) = 2$ and $\hat{\beta}(0) = 6$.

We take the initial values of the master system (1) as $x(0) = (15, 24, 18)$.

We take the initial values of the slave system (2) as $y(0) = (22, 40, 10)$.

Figure 2 shows the adaptive chaos synchronization of the identical Moore-Spiegel systems. Figure 3 shows that the estimated values of the parameters $\hat{\alpha}$ and $\hat{\beta}$ converge to the system parameters $\alpha = 6$ and $\beta = 20$.
3. ADAPTIVE SYNCHRONIZATION OF IDENTICAL ACT SYSTEMS

3.1 Theoretical Results

In this section, we discuss the adaptive synchronization of identical ACT systems (Arneodo, Coullet and Tresser, [19], 1981) with unknown parameters.

As the master system, we consider the ACT dynamics described by

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= ax_1 - bx_2 - x_3 - x_1^2
\end{align*}
\]  

(14)

where \(x_1, x_2, x_3\) are the states and \(a, b\) are unknown system parameters.

The system (14) is chaotic when the parameter values are taken as \(a = 7.5\) and \(b = 3.8\).

As the slave system, we consider the controlled ACT dynamics described by

\[
\begin{align*}
\dot{y}_1 &= y_2 + u_1 \\
\dot{y}_2 &= y_3 + u_2 \\
\dot{y}_3 &= ay_1 - by_2 - y_3 - y_1^2 + u_3
\end{align*}
\]  

(15)

where \(y_1, y_2, y_3\) are the states and \(u_1, u_2, u_3\) are the nonlinear controllers to be designed.
The strange attractor of the ACT chaotic system (14) is shown in Figure 4.

The synchronization error is defined by

\[ e_i = y_i - x_i, \quad (i = 1, 2, 3) \]  \hspace{1cm} (16)

The error dynamics is easily obtained as

\[ \dot{e}_1 = e_2 + u_1 \]
\[ \dot{e}_2 = e_3 + u_2 \]
\[ \dot{e}_3 = ae_1 - be_2 - e_3 - y_1^2 + x_1^2 + u_3 \]  \hspace{1cm} (17)

Let us now define the adaptive control functions \( u_1(t), u_2(t), u_3(t) \) as

\[ u_1 = -e_2 - k_1 e_1 \]
\[ u_2 = -e_3 - k_2 e_2 \]
\[ u_3 = -\hat{a} e_1 + \hat{b} e_2 + e_3 + y_1^2 - x_1^2 - k_e e_3 \]  \hspace{1cm} (18)

where \( \hat{a} \) and \( \hat{b} \) are estimates of the parameters \( a \) and \( b \) respectively, and \( k_e, (i = 1, 2, 3) \) are positive constants.
Substituting the control law (18) into (17), we obtain the error dynamics as

\[
\begin{align*}
\dot{e}_1 &= -k_1 e_1 \\
\dot{e}_2 &= -k_2 e_2 \\
\dot{e}_3 &= (a - \hat{a}) e_1 - (b - \hat{b}) e_2 - k_3 e_3
\end{align*}
\]

(19)

Let us now define the parameter errors as

\[
e_a = a - \hat{a} \quad \text{and} \quad e_b = b - \hat{b}
\]

(20)

Substituting (20) into (19), the error dynamics simplifies to

\[
\begin{align*}
\dot{e}_1 &= -k_1 e_1 \\
\dot{e}_2 &= -k_2 e_2 \\
\dot{e}_3 &= e_a e_1 - e_b e_2 - k_3 e_3
\end{align*}
\]

(21)

For the derivation of the update law for adjusting the estimates of the parameters, the Lyapunov approach is used. Consider the quadratic Lyapunov function

\[
V = \frac{1}{2} \left( e_1^2 + e_2^2 + e_3^2 + e_a^2 + e_b^2 \right)
\]

(22)

Note also that

\[
\dot{e}_a = -\dot{a} \quad \text{and} \quad \dot{e}_b = -\dot{b}
\]

(23)

Differentiating \( V \) along the trajectories of (22) and using (21), we obtain

\[
\dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 + e_a \left[ e_1 e_3 - \dot{a} \right] + e_b \left[ -e_2 e_3 - \dot{b} \right]
\]

(24)

In view of Eq. (24), the estimated parameters are updated by the following law:

\[
\begin{align*}
\dot{a} &= e_1 e_3 + k_4 e_a \\
\dot{b} &= -e_2 e_3 + k_4 e_b
\end{align*}
\]

(25)

where \( k_4, k_5 \) are positive constants.

Substituting (25) into (24), we get

\[
\dot{V} = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 - k_4 e_a^2 - k_5 e_b^2,
\]

(26)

which is a negative definite function on \( \mathbb{R}^5 \).

Thus, by Lyapunov stability theory [20], it is immediate that the synchronization error and the parameter error decay to zero exponentially with time for all initial conditions.
Hence, we have proved the following result.

**Theorem 2.** The identical ACT systems (14) and (15) with unknown parameters are globally and exponentially synchronized for all initial conditions by the adaptive control law (18), where the update law for parameters is given by (25) and $k_i, (i = 1, \ldots, 5)$ are positive constants.

### 3.2 Numerical Results

For the numerical simulations, the fourth order Runge-Kutta method is used to solve the two systems of differential equations (14) and (15) with the adaptive control law (18) and the parameter update law (25).

For the adaptive synchronization of the ACT systems with parameter values $a = 7.5$, $b = 3.8$, we apply the adaptive control law (18) and the parameter update law (25). We take the positive constants $k_i, (i = 1, \ldots, 5)$ as $k_i = 2$ for $i = 1, 2, \ldots, 5$. Suppose that the initial values of the estimated parameters are $\hat{a}(0) = 5$ and $\hat{b}(0) = 7$.

We take the initial values of the master system (14) as $x(0) = (9, 2, 12)$. We take the initial values of the slave system (15) as $y(0) = (4, 8, 3)$.

Figure 5 shows the adaptive chaos synchronization of the identical ACT systems. Figure 6 shows that the estimated values of the parameters $\hat{a}$ and $\hat{b}$ converge to the system parameters $a = 7.5$ and $b = 3.8$.  

Figure 4. Adaptive Synchronization of the Identical ACT Systems
4. ADAPTIVE SYNCHRONIZATION OF MOORE-SPIEGEL AND ACT SYSTEMS

4.1 Theoretical Results

In this section, we discuss the adaptive synchronization of non-identical Moore-Spiegel system ([18], 1966) and ACT chaotic system ([19], 1981) with unknown parameters.

As the master system, we consider the Moore-Spiegel dynamics described by

$$\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= -(1-x_1)(1+\alpha x_1^2)x_2 - \beta x_1
\end{align*}$$

(27)

where $x_1, x_2, x_3$ are the states and $\alpha, \beta$ are unknown system parameters.

As the slave system, we consider the controlled ACT dynamics described by

$$\begin{align*}
\dot{y}_1 &= y_2 + u_1 \\
\dot{y}_2 &= y_3 + u_2 \\
\dot{y}_3 &= ay_1 - by_2 - y_3 - y_1^2 + u_3
\end{align*}$$

(28)

where $y_1, y_2, y_3$ are the states, $a, b$ are unknown system parameters and $u_1, u_2, u_3$ are the nonlinear controllers to be designed.
The synchronization error is defined by

\[ e_i = y_i - x_i, \quad (i = 1, 2, 3) \tag{29} \]

The error dynamics is easily obtained as

\[ \dot{e}_1 = e_2 + u_1 \]
\[ \dot{e}_2 = e_3 + u_2 \]
\[ \dot{e}_3 = a e_1 - b e_2 - e_3 + (a + \beta)x_1 + (\beta - \alpha - b)x_2 - y_1^2 + \alpha x_1^2 x_2 + u_3 \tag{30} \]

Let us now define the adaptive control functions \( u_1(t), u_2(t), u_3(t) \) as

\[ u_1 = -e_2 - k_1 e_1 \]
\[ u_2 = -e_3 - k_2 e_2 \]
\[ u_3 = -\hat{\alpha} e_1 + \hat{b} e_2 + e_3 - (\hat{\alpha} + \hat{\beta})x_1 - (\hat{\beta} - \hat{\alpha} - \hat{b})x_2 + y_1^2 - \hat{\alpha} x_1^2 x_2 - k_3 e_3 \tag{31} \]

where \( \hat{\alpha}, \hat{\beta}, \hat{\alpha} \) and \( \hat{b} \) are estimates of the parameters \( \alpha, \beta, a \) and \( b \) respectively, and \( k_i, (i = 1, 2, 3) \) are positive constants.

Substituting the control law (31) into (30), we obtain the error dynamics as

\[ \dot{e}_1 = -k_1 e_1 \]
\[ \dot{e}_2 = -k_2 e_2 \]
\[ \dot{e}_3 = (a - \hat{\alpha}) e_1 - (b - \hat{b}) e_2 + [(a - \hat{\alpha}) + (\beta - \hat{\beta})] x_1 + [(\beta - \hat{\beta}) - (\alpha - \hat{\alpha}) - (b - \hat{b})] x_2 + (\alpha - \hat{\alpha}) x_1^2 x_2 - k_3 e_3 \tag{32} \]

Let us now define the parameter errors as

\[ e_\alpha = \alpha - \hat{\alpha}, \quad e_\beta = \beta - \hat{\beta}, \quad e_a = a - \hat{\alpha}, \quad e_b = b - \hat{b} \tag{33} \]

Substituting (33) into (32), the error dynamics simplifies to

\[ \dot{e}_1 = -k_1 e_1 \]
\[ \dot{e}_2 = -k_2 e_2 \]
\[ \dot{e}_3 = e_\alpha e_1 - e_\beta e_2 + [e_\alpha + e_\beta] x_1 + [e_\beta - e_\alpha] x_2 + e_a x_1^2 x_2 - k_3 e_3 \tag{34} \]

For the derivation of the update law for adjusting the estimates of the parameters, the Lyapunov approach is used. Consider the quadratic Lyapunov function

\[ V = \frac{1}{2} \left( e_1^2 + e_2^2 + e_3^2 + e_\alpha^2 + e_\beta^2 + e_a^2 + e_b^2 \right) \tag{35} \]
Note also that

\[
\begin{align*}
\dot{e}_a &= -\dot{\alpha}, \quad \dot{e}_b = -\dot{\beta}, \quad \dot{\alpha} = -\dot{\alpha}, \quad \dot{\beta} = -\dot{\beta}
\end{align*}
\]  

(36)

Differentiating \( V \) along the trajectories of (34) and using (36), we obtain

\[
\dot{V} = -k_1 e_a^2 - k_2 e_b^2 - k_3 e_a^2 + e_a \left(e_a x_2 \left(x_1^2 - 1\right) - \dot{\alpha}\right) + e_\beta \left(e_\beta (x_1 + x_2) - \dot{\beta}\right)
\]

\[
+ e_a \left(e_\alpha y_1 - \dot{\alpha} \right) + e_b \left[-e_\beta y_2 - \dot{\beta}\right]
\]

(37)

In view of Eq. (37), the estimated parameters are updated by the following law:

\[
\begin{align*}
\dot{\alpha} &= e_\alpha x_2 \left(x_1^2 - 1\right) + k_4 e_a \\
\dot{\beta} &= e_\beta (x_1 + x_2) + k_5 e_\beta \\
\dot{\alpha} &= e_{\alpha} y_1 + k_6 e_a \\
\dot{\beta} &= -e_{\beta} y_2 + k_7 e_b
\end{align*}
\]  

(38)

where \( k_4, k_5, k_6, k_7 \) are positive constants.

Substituting (38) into (37), we get

\[
\dot{V} = -k_1 e_a^2 - k_2 e_b^2 - k_3 e_a^2 - k_4 e_a^2 - k_5 e_\beta^2 - k_6 e_a^2 - k_7 e_b^2,
\]

(39)

which is a negative definite function on \( \mathbb{R}^7 \).

Thus, by Lyapunov stability theory [20], it is immediate that the synchronization error and the parameter error decay to zero exponentially with time for all initial conditions.

Hence, we have proved the following result.

**Theorem 3.** The non-identical Moore-Spiegel system (27) and ACT system (28) with unknown parameters are globally and exponentially synchronized for all initial conditions by the adaptive control law (31), where the update law for parameters is given by (38) and \( k_i, (i = 1, \ldots, 7) \) are positive constants.

### 4.2 Numerical Results

For the numerical simulations, the fourth order Runge-Kutta method is used to solve the two systems of differential equations (27) and (28) with the adaptive control law (31) and the parameter update law (38).

In the chaotic case, the parameter values for the Moore-Spiegel and ACT systems are

\[
\alpha = 6, \quad \beta = 20, \quad a = 7.5, \quad b = 3.8
\]
We take the positive constants $k_i, (i = 1, \ldots, 7)$ as

$$k_i = 2 \text{ for } i = 1, 2, \ldots, 7.$$  

Suppose that the initial values of the estimated parameters are

$$\hat{\alpha}(0) = 7, \quad \hat{\beta}(0) = 2, \quad \hat{a}(0) = 10 \quad \text{and} \quad \hat{b}(0) = 8.$$  

We take the initial values of the master system (14) as $x(0) = (12, 4, 6)$.  

We take the initial values of the slave system (15) as $y(0) = (2, 28, 20)$.  

Figure 7 shows the adaptive chaos synchronization of the identical ACT systems.

Figure 8 shows that the estimated values of the parameters $\hat{\alpha}, \hat{\beta}, \hat{a}$ and $\hat{b}$ converge to the system parameters $\alpha = 6, \beta = 20, a = 7.5$ and $b = 3.8$.  

![Figure 7. Adaptive Synchronization of the Moore-Spiegel and ACT Systems](image-url)
5. CONCLUSIONS

In this paper, we applied adaptive control theory to derive synchronizing feedback control schemes for the global chaos synchronization of identical Moore-Spiegel systems (1966), identical ACT systems (1981) and non-identical Moore-Spiegel and ACT systems. In adaptive synchronization of chaotic systems, the parameters of the master and slave systems are unknown and we devise feedback control laws using the estimates of the system parameters. The adaptive control method is very useful in practical applications. The adaptive synchronization results derived in this paper are established using Lyapunov stability theory. Since Lyapunov exponents are not required for these calculations, the adaptive control method is very effective and convenient to achieve global chaos synchronization for the uncertain Moore-Spiegel and ACT chaotic systems. Numerical simulations are also shown to demonstrate the effectiveness of the adaptive synchronization schemes derived in this paper.

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