A Fractional-Order System with Coexisting Chaotic Attractors and Control Chaos via a Single State Variable Linear Controller

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1. Introduction

Chaotic behaviors in nonlinear is a very interesting phenomenon. The high irregularity, unpredictability, and complexity in chaotic systems [1, 2] have been widely used in the field of engineering and technology such as secure communications, image steganography, authenticated encryption, motor control, and power system protection. Recently, coexisting chaotic attractors have been found in chaotic systems [3–9]. For example, the coexisting chaotic attractors in a 3D no-equilibrium system were reported by Pham et al. [3], the coexisting multiple attractors in Hopfield neural network were found by Bao et al. [4], the coexisting chaotic attractors in a hyperchaotic hyperjerk system were given by Wang et al. [5], the coexisting "positive attractor" and "negative attractor" in a 3D autonomous continuous chaotic system were found by Zhou and Ke [6], and so on [7–9]. Therefore, more and more attention has been focused on the coexisting chaotic attractors in nonlinear chaotic systems.

On the other hand, the fractional-order differential equations [10–12] can be accurately described in the real-world physical systems such as viscoelasticity, dielectric polarization, electrode-electrolyte polarization, electromagnetic waves, heat conduction, diffusion-wave, and superdiffusion. Chaotic behaviors have been found in many real-world physical fractional-order nonlinear systems, for example, the fractional-order chaotic brushless DC motor [13], the fractional-order electronic circuits [14], the fractional-order microelectromechanical system [15], and the fractional-order gyroscopes [16]. Therefore, more and more attention has been paid to the chaotic behaviors in fractional-order nonlinear systems.

Motivated by the above discussions, based on a 3D autonomous continuous chaotic system reported by Zhou and Ke [6], we suggested a 3D autonomous continuous fractional-order system. We have shown that the chaotic system reported by Zhou and Ke [6] can be extended to its fractional-order version where the coexisting "positive attractor" and "negative attractor" can be observed. We obtained that the fractional-order system with the order as low as 2.5431 exhibits chaotic attractors. Moreover, we obtained the largest Lyapunov exponent varying as fractional order. Finally, for the stabilization of the unstable equilibrium, one control scheme is proposed via a single state variable linear controller.
The outline of this paper is organized as follows. In Section 2, based on a 3D autonomous continuous chaotic system reported by Zhou and Ke [6], the fractional-order version nonlinear system is given, and some basic dynamical properties of this fractional-order version nonlinear system are obtained including the necessary condition of the existence chaos, the largest Lyapunov exponent varying as fractional order, and the coexisting “positive attractor” and “negative attractor.” In Section 3, by a single state variable, stabilization of the unstable equilibrium points of the fractional-order chaotic system is discussed. Finally, the conclusions are given in Section 4.

2. System Model and Basic Characteristics

In this paper, the Caputo definition of the fractional derivative will be used in next. The Caputo definition of the fractional derivative is described as

\[
\frac{\xi D_t^q g(t)}{\Gamma(k - q)} = \frac{1}{\Gamma(k - q)} \int_0^t (t - \tau)^{k - q - 1} g^{(k)}(\tau) \, d\tau,
\]

\( k - 1 < q < k, \) 

where \( \xi D_t^q \) is the Caputo operator, \( k \) is the first integer which is not less than \( q \), and \( g^{(k)}(t) \) is the \( k \)-order derivative in usual sense of \( g(t) \).

Next, based on the 3D autonomous continuous chaotic system reported by Zhou and Ke [6], a fractional-order system is addressed as

\[
\begin{align*}
\frac{d}{dt} S_1 &= -x_1 + 0.5x_1 x_3 + x_2 x_3, \\
\frac{d}{dt} S_2 &= 4x_2 - 1.2x_1 x_3, \\
\frac{d}{dt} S_3 &= x_1 x_2 - 6x_3,
\end{align*}
\]

where fractional order \( 0 < q < 1 \). Fractional-order system (2) has five equilibrium points. They are \( S_0 = (0, 0, 0), S_1^+ = (4.4721, -1.5745, 1.1736), S_1^- = (-4.4721, 1.5745, 1.1736), S_2^+ = (4.4721, 3.8106, -2.8403), \) and \( S_2^- = (-4.4721, -3.8106, -2.8403) \), respectively.

Now, we can obtain the eigenvalues of the five equilibrium points. The eigenvalues of equilibrium point \( S_0 \) are \((-6, -1, 4)\). Thus, equilibrium point \( S_0 \) is an unstable saddle point of index one. The eigenvalues of equilibrium points \( S_1^+ \) and \( S_1^- \) are \((-5.3957, 1.4912 + 3.2168j, 1.4912 - 3.2168j)\). Thus, equilibrium points \( S_1^+ \) and \( S_1^- \) are unstable saddle points of index two. The eigenvalues of equilibrium points \( S_2^+ \) and \( S_2^- \) are \((-6.7558, 1.1678 + 4.7892j, 1.1678 - 4.7892j)\). Thus, equilibrium points \( S_2^+ \) and \( S_2^- \) are unstable saddle points of index two.

Tavazoei and Haeri [17] have obtained that a necessary condition for a fractional-order nonlinear system to exist chaotic is

\[
q \geq \frac{2}{\pi} \arctan \left( \frac{\text{Im} (\lambda)}{\text{Re} (\lambda)} \right),
\]

where \( \lambda \) is the eigenvalues of saddle equilibrium point of index two in fractional-order nonlinear system.

Thus, the necessary condition of existence chaos in fractional-order system (2) is \( q \geq 0.7237 \). This result indicates that fractional-order system (2) with the order as low as 2.5431 can exhibit chaotic attractors.

In this paper, the improved version of Adams-Bashforth-Moulton [18] (denoted by IVABM) numerical algorithm is used to deal with fractional-order system (2). The IVABM numerical algorithm will be introduced next. Now, consider the fractional-order system

\[
\begin{align*}
\frac{\xi D_t^q x_1}{\Gamma(q_1 + 2)} &= g_1 \left( x_1 (n + 1), x_2 (n + 1), x_3 (n + 1) \right), \\
\frac{\xi D_t^q x_2}{\Gamma(q_2 + 2)} &= g_2 \left( x_1 (n + 1), x_2 (n + 1), x_3 (n + 1) \right), \\
\frac{\xi D_t^q x_3}{\Gamma(q_3 + 2)} &= g_3 \left( x_1 (n + 1), x_2 (n + 1), x_3 (n + 1) \right),
\end{align*}
\]

with initial condition \( (x_1(0), x_2(0), x_3(0)) \). Let \( l = T/N \), and \( t_n = nl \ (n = 0, 1, 2, \ldots, N) \). By IVABM numerical algorithm, system (5) can be discretized as follows:

\[
\begin{align*}
x_1 (n + 1) &= x_1 (0) \\
&\quad + \frac{H_l}{\Gamma(q_1 + 2)} \left[ g_1 \left( x_1^p (n + 1), x_2^p (n + 1), x_3^p (n + 1) \right) \right], \\
x_2 (n + 1) &= x_2 (0) \\
&\quad + \frac{H_l}{\Gamma(q_2 + 2)} \left[ g_2 \left( x_1^p (n + 1), x_2^p (n + 1), x_3^p (n + 1) \right) \right], \\
x_3 (n + 1) &= x_3 (0) \\
&\quad + \frac{H_l}{\Gamma(q_3 + 2)} \left[ g_3 \left( x_1^p (n + 1), x_2^p (n + 1), x_3^p (n + 1) \right) \right] + \sum_{j=0}^{n} \alpha_{3,j+1} g_3 \left( x_1 (j), x_2 (j), x_3 (j) \right),
\end{align*}
\]
via an IVABM numerical algorithm, which is shown in Figure 1, the fractional-order system (2) for the chaotic attractor is emerged in fractional-order system (2). The chaotic attractor in fractional-order system (2) can be decided by the initial conditions; that is, the chaotic attractor depends on the distance from the initial point (initial condition \( x_0 = (x_1(0), x_2(0), x_3(0)) \) to the unstable points [6]. Next, the distances from the initial point to points \( S_1^r, S_1^l, S_2^r, \) and \( S_2^l \) are denoted by \( L_1^r, L_1^l, L_2^r, \) and \( L_2^l, \) respectively. Same as [6], the following results can be obtained:

1. If the initial point (initial condition) is near the unstable \( S_1^r \) or \( S_1^l, \) there is the same chaotic attractor in fractional-order chaotic system (2), which is called “positive attractor” by Zhou and Ke [6], where the “positive attractor” means \( x(t) > 0 \) and a necessary condition for “positive attractor” is \( x_1(0) > 0 \) [6].

2. If the initial point (initial condition) is near the unstable \( S_2^r \) or \( S_2^l, \) there is the same chaotic attractor in fractional-order chaotic system (2), which is called “negative attractor” by Zhou and Ke [6], where the “positive attractor” means \( x(t) < 0 \) and a necessary condition for “negative attractor” is \( x_1(0) < 0 \) [6].

Next, some numerical simulations are given for \( q = 0.9 \).

Here, the largest Lyapunov exponent is 0.763 for \( q = 0.9 \).

Case 1 (the initial point is near unstable saddle point \( S_1^r \) or \( S_1^l \)). For example, choose the initial conditions as \((-4, 1, 1)\). Therefore, \( L_1^r, L_1^l, L_2^r, \) and \( L_2^l \) are 8.8563, 0.7636, 9.7172, and 6.1735, respectively. Therefore, the initial point \((-4, 1, 1)\) is near unstable saddle point \( S_1^r \). Therefore, the fractional-order system (2) has the “positive attractor,” which is shown as Figure 3.

For example, choose the initial conditions as \((-4, 1, 1)\). Therefore, \( L_1^r, L_1^l, L_2^r, \) and \( L_2^l \) are 8.8563, 0.7636, 9.7172, and 6.1735, respectively. Therefore, the initial point \((-4, 1, 1)\) is near unstable saddle point \( S_1^l \). Thus, fractional-order system (2) has the “negative attractor,” which is shown as Figure 3.

Case 2 (the initial point is near unstable saddle point \( S_1^r \) or \( S_1^l \)). For example, choose the initial conditions as \((4, 3, -2)\). Therefore, \( L_1^r, L_1^l, L_2^r, \) and \( L_2^l \) are 5.8875, 9.1586, 1.2594, and 10.9026, respectively. Therefore, the initial point \((4, 3, -2)\) is close to unstable saddle point \( S_2^r \). Thus, fractional-order system (2) has the “positive attractor,” which is shown as Figure 4.

For example, choose the initial conditions as \((4, 3, -2)\). Therefore, \( L_1^r, L_1^l, L_2^r, \) and \( L_2^l \) are 5.8875, 9.1586, 1.2594, and 10.9026, respectively. Therefore, the initial point \((4, 3, -2)\) is close to unstable saddle point \( S_2^r \). Thus, fractional-order system (2) has the “negative attractor,” which is shown as Figure 4.

According to Figures 3 and 4, the coexisting chaotic attractors are found in fractional-order chaotic system (2). These results indicate that the chaotic system reported by Zhou and Ke [6] can be extended to its fractional-order version where the coexisting “positive attractor” and “negative attractor” can be observed.

Remark 1. There are overlaps between the coexisting chaotic attractors in [3–5, 7–9]. However, there are two isolated chaotic attractors in fractional-order chaotic system.
Figure 2: The chaotic attractor in fractional-order system (2).

Figure 3: The “positive attractor” and “negative attractor” in fractional-order system (2).

Figure 4: The “positive attractor” and “negative attractor” in fractional-order system (2).

3. Stabilization of the Unstable Equilibrium Points of the Fractional-Order Chaotic System (2)

First, a result on stability of fractional-order nonlinear system is recalled. Consider the fractional-order nonlinear system as follows:

\[ \dot{y}(t) = H(y(t)) = My(t) + f(y(t)), \quad (9) \]

where \(0 < q \leq 1\), \(y(t) = (y_1(t), y_2(t), \ldots, y_n(t))^T \in \mathbb{R}^n\) denotes the state vector, \(H : \mathbb{R}^n \to \mathbb{R}^n\) is a nonlinear vector field, \(M \in \mathbb{R}^{n \times n}\) is a constant matrix, and \(f(y(t))\) and \(My(t)\) denote the nonlinear and linear parts of \(H(y(t))\).

Lemma 2 (for more details, see [19]). Fractional-order nonlinear system (9) is said to be asymptotically stable if the next two conditions hold:

(i) \( f(y(t))|_{y(t)=0} = 0\), and \( \lim_{y(t) \to 0} (\|f(y(t))\|/\|y(t)\|) = 0 \),

(ii) \(|\arg \lambda_i(M)| > 0.5 q \pi (i = 1, 2, \ldots, n)\), and \(q\|M\| > 1\), where \(\lambda_i(M)\) and \(\|M\|\) denote the eigenvalues and the \(l_2\)-norm with respect to matrix \(M\), respectively.
Next, we discuss how to stabilize the unstable equilibrium point in fractional-order chaotic system (2) via single state variable linear controller. Now, let the unstable equilibrium points in system (2) be \((\bar{x}_1, \bar{x}_2, \bar{x}_3)\), and the controlled fractional-order system is shown as follows:

\[
\begin{align*}
\dot{x}_1(t) &= -x_1 + 0.5x_1x_3 + x_2x_3 + k_1 (x_2 - \bar{x}_2), \\
\dot{x}_2(t) &= 4x_2 - 1.2x_1x_3 + k_2 (x_2 - \bar{x}_2), \\
\dot{x}_3(t) &= x_1x_2 - 6x_3 + k_3 (x_2 - \bar{x}_2),
\end{align*}
\]

(10)

where \(0.8477 \leq q \leq 1\) and \(k_i(x_2 - \bar{x}_2)\) \((i = 1, 2, 3)\) is a linear controller determined by a single state variable \(x_2\). \(k_i\) \((i = 1, 2, 3)\) \(\in R\) are feedback gains determined later.

**Theorem 3.** Let real matrix be

\[
A = \begin{pmatrix}
-(1 - 0.5\bar{x}_3) & (0.5\bar{x}_1 + \bar{x}_2) \\
-1.2\bar{x}_3 & (4 + k_2) & 1.2\bar{x}_1 \\
\bar{x}_2 & (x_1 + k_3) & -6
\end{pmatrix},
\]

(11)

and choose suit feedback gains \(k_i\) \((i = 1, 2, 3)\); if \(|\arg \lambda_i(A)| > 0.5\pi\) \((i = 1, 2, 3)\), then the unstable equilibrium points \((\bar{x}_1, \bar{x}_2, \bar{x}_3)\) of fractional-order chaotic system (2) in controlled system (10) are asymptotically stable.

**Proof.** Let \(y_1 = x_1 - \bar{x}_1, y_2 = x_2 - \bar{x}_2, y_3 = x_3 - \bar{x}_3\); then controlled system (10) can be changed as

\[
\begin{align*}
\dot{y}_1(t) &= -(1 - 0.5\bar{x}_3) y_1 + (\bar{x}_1 + k_1) y_2 \\
&\quad + (0.5\bar{x}_1 + \bar{x}_2) y_3 + 0.5 y_1 y_3 + y_2 y_3, \\
\dot{y}_2(t) &= -1.2\bar{x}_3 y_1 + (4 + k_2) y_2 - 1.2\bar{x}_1 y_3 - 1.2 y_1 y_3, \\
\dot{y}_3(t) &= \bar{x}_2 y_1 + (x_1 + k_3) y_2 - 6 y_3 + y_1 y_2.
\end{align*}
\]

(12)

Thus, the unstable equilibrium points \((\bar{x}_1, \bar{x}_2, \bar{x}_3)\) in fractional-order chaotic system (2) are changed as the point \((y_1, y_2, y_3) = (0, 0, 0)\) in system (12).

One can easily obtain that point \((y_1, y_2, y_3) = (0, 0, 0)\) is the origin of system (12). Therefore, the problem of stabilization of the unstable equilibrium points in fractional-order chaotic system (2) is turned to the problem of stabilization of fractional-order system (12). If the origin of system (12) is asymptotically stable, then the unstable equilibrium points \((\bar{x}_1, \bar{x}_2, \bar{x}_3)\) of fractional-order chaotic system (2) in controlled system (10) are asymptotically stable.

Now, controlled system (12) can be rewritten as

\[
\dot{y}(t) = Ay(t) + f(y(t)),
\]

(13)

where \(f(y(t)) = ((0.5y_1 + y_2)y_3 - 1.2y_1y_3 y_1y_2)^T\).

First, it is easy to obtain that \(f(y(t))|_{y(t)=0} = 0\), and

\[
\lim_{y(t) \to 0} \frac{\|f(y(t))\|}{\|y(t)\|} = \frac{\sqrt{((0.5y_1 + y_2)y_3)^2 + (-1.2y_1y_3)^2 + (y_1y_2)^2}}{y_1^2 + y_2^2 + y_3^2}
\]

\(\leq \sqrt{((0.5y_1 + y_2)^2 + (-1.2y_1y_3)^2 + (y_1y_2)^2},
\]

(14)

Thus, the first condition in Lemma 2 is satisfied.

Second, according to

\[
A = \begin{pmatrix}
-(1 - 0.5\bar{x}_3) & (0.5\bar{x}_1 + \bar{x}_2) \\
-1.2\bar{x}_3 & (4 + k_2) & 1.2\bar{x}_1 \\
\bar{x}_2 & (x_1 + k_3) & -6
\end{pmatrix},
\]

(15)

\(q\|A\| > 1\), and using \(|\arg \lambda_i(A)| > 0.5\pi\) \((i = 1, 2, 3)\), we can yield that the second condition in Lemma 2 is satisfied.

Therefore, according to Lemma 2, the origin of system (12) is asymptotically stable. That is, the unstable equilibrium points \((\bar{x}_1, \bar{x}_2, \bar{x}_3)\) of fractional-order chaotic system (2) in controlled system (10) are asymptotically stable. The proof is finished.

**Remark 4.** In our control scheme, the linear controller is only determined by one single state variable, so our control scheme is different from many previous control schemes.

### 4. Numerical Simulations Results

Next, in order to show the effectiveness of the proposed control approach, the numerical simulations are performed for \(q = 0.9\).

For the unstable equilibrium point \(S_0 = (0, 0, 0)\), if we choose \(k_1 = k_3 = 0, k_2 = -7\), then \(A = \begin{pmatrix} -3 & 0 & 0 \\ 0 & -3 & 0 \\ 0 & 0 & -6 \end{pmatrix}\). Thus, we obtain \(\lambda_1 = -1, \lambda_2 = -3, \lambda_3 = -6\), and \(q\|A\| > 1\). According to Theorem 3, the unstable equilibrium point \(S_0\) in controlled system (10) is asymptotically stable. Figure 5 displays the time evolution of state variables. Here, the initial conditions be \((7, 6, 3)\).

For the unstable equilibrium point \(S_1 = (4.4721, -1.5745, 1.1736)\), if we choose \(k_1 = k_3 = 0, k_2 = -8\), then \(A = \begin{pmatrix} -0.4132 & 1.1736 & 0.6615 \\ -1.4083 & -6 & 5.3665 \\ -1.5745 & 4.4721 & -6 \end{pmatrix}\). Thus, we obtain \(\lambda_1 = -0.5726, \lambda_{2,3} = -4.9203 \pm 4.9982j\), and \(q\|A\| > 1\). According
to Theorem 3, the unstable equilibrium point $S^+_1$ in controlled system (10) is asymptotically stable. Figure 6 shows the time evolution of state variables. Here, the initial conditions are $(2.4, 2)$.

For the unstable equilibrium point $S^-_1 = (-4.4721, 1.5745, 1.1736)$, if we choose $k_1 = k_3 = 0, k_2 = -4$, then $A = \left( \begin{array}{ccc} -0.4132 & 1.1736 & -0.6615 \\ -1.0493 & 0 & -5.3665 \\ -4.4721 & -6 & 0 \end{array} \right)$. Therefore, we obtain $\lambda_1 = -0.5418, \lambda_{2,3} = -2.9357 \pm 4.1682j$, and $q\|A\| > 1$. According to Theorem 3, the unstable equilibrium point $S^+_1$ in controlled system (10) is asymptotically stable. Figure 7 shows the time evolution of state variables. Here, the initial conditions are $(1, 7, 2)$.

For the unstable equilibrium point $S^-_1 = (4.4721, 3.8106, -2.8403)$, if we choose $k_1 = -2.1597, k_2 = -7, k_3 = -9.4721$, then $A = \left( \begin{array}{ccc} -2.4201 & -5 & 6.0466 \\ 3.40836 & -3 & 5.36652 \\ -3.8106 & 5 & -6 \end{array} \right)$. Thus, we obtain $\lambda_1 = -10.8877, \lambda_{2,3} = -0.2662 \pm 1.040j$, and $q\|A\| > 1$. According to Theorem 3, the unstable equilibrium point $S^+_1$ in controlled system (10) is asymptotically stable. Figure 8 shows the time evolution of state variables. Here, the initial conditions are $(5, 4, -3)$.

For the unstable equilibrium point $S^-_1 = (-4.4721, -3.8106, -2.8403)$, if we choose $k_1 = -7.1597, k_2 = -7, k_3 = 9.9721$, then $A = \left( \begin{array}{ccc} -2.4201 & -5 & -6.0466 \\ 3.40836 & -3 & 5.36652 \\ -3.8106 & -5 & 6 \end{array} \right)$. Thus, we obtain $\lambda_1 = -9.3229, \lambda_{2,3} = -1.0486 \pm 0.8095j$, and $q\|A\| > 1$. According to Theorem 3, the unstable equilibrium point $S^+_1$ in controlled system (10) is asymptotically stable. Figure 9 shows the time evolution of state variables. Here, the initial conditions are $(-7, -6, -2)$.

The simulative results in Figures 5–9 show the effectiveness of our control scheme.

5. Conclusions

In this paper, a fractional-order chaotic system is proposed. The necessary condition of existence chaos in this fractional-order chaotic system is $q \geq 0.8477$. The largest Lyapunov exponent varying as fractional order $q$ is given. The coexisting “positive attractor” and “negative attractor” can be observed, and the necessary conditions for “positive attractor” and “negative attractor” are obtained. Meanwhile, by a single state variable, a linear controller is used for the stabilization of the unstable equilibrium points of the fractional-order chaotic system. The numerical results show that the control approach is effective.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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