1. INTRODUCTION

Hyperchaos was first proposed by Otto Rössler in 1979 [1]. Since then, many novel hyperchaotic systems have been formulated. To obtain hyperchaos, the system need to satisfy the following two important requisites. Firstly, the minimal dimension of the phase space that embeds a hyperchaotic attractor should be at least four, which requires the minimum number of coupled first-order autonomous ordinary differential equations to be four. Secondly, the number of terms in the coupled equations giving rise to instability should be at least two, of which at least one should have a nonlinear function [2]. Therefore, hyperchaos is much more complicated than chaos, and it has greater engineering significance and application prospect in signal processing, secure communication and so on.

In this paper, a novel 5D hyperchaotic system, which has been introduced in Wei and Niu [3], is reviewed. Stability control of the 5D system would be discussed, and some simulation results would be given to demonstrate the validity of the designed linear feedback controllers.

2. THE NOVEL 5D HYPERCHAOTIC SYSTEM

The dynamic equations of the novel 5D hyperchaotic system are formulated as

\[
\begin{align*}
\dot{x} &= a(y - x), \\
\dot{y} &= (c - a)x + cy + w - xz, \\
\dot{z} &= -bz + xy, \\
\dot{v} &= mw, \\
\dot{w} &= -y - hv,
\end{align*}
\]  

(1)

where \(x, y, z, v, w \in \mathbb{R}\) are state variables, and \(a = 23, b = 3, c = 18, m = 12\) and \(h = 4\) [3]. Let the initial values of the 5D system (1) be \((x_0, y_0, z_0, v_0, w_0) = (1, 1, 1, 1, 1)\), then the Lyapunov exponents respectively are \(\lambda_1 = 0.8732 > 0, \lambda_2 = 0.1282 > 0, \lambda_3 = -0.0013 \approx 0, \lambda_4 = -0.5770 < 0\) and \(\lambda_5 = -8.4231 < 0\). It indicates that the 5D system (1) is hyperchaotic. The attractors of the 5D hyperchaotic system (1) are shown in Figure 1.

3. HYPERCHAOS CONTROL OF THE 5D SYSTEM

3.1. Formulation of the Controlled System

Theorem 1. Let \(x = 0\) be an equilibrium point for \(\dot{x} = f(x)\), where \(f: D \to \mathbb{R}^n\) is a locally Lipschitz map from a domain \(D \subset \mathbb{R}^n\) into \(\mathbb{R}^n\). Let \(V: \mathbb{R}^n \to \mathbb{R}\) be a continuously differentiable function such that
Figure 1 Attractors of the 5D hyperchaotic system: (a1) z-x-y; (a2) v-x-y; (a3) w-x-y; (a4) v-w-z; (a5) x-w-z; (a6) w-x-v.

\[
V(0) = 0 \quad \text{and} \quad V(x) > 0, \quad \forall x \neq 0
\]

\[
\lim_{x \to \infty} V(x) \to \infty
\]

\[
V(x) < 0, \quad \forall x \neq 0
\]

then \( x = 0 \) is globally asymptotically stable [4].

From Theorem 1, take a continuously differentiable function

\[
V = \frac{1}{2} \left( x^2 + y^2 + z^2 + \frac{h}{m} v^2 + w^2 \right)
\]

as a Lyapunov function candidate for the controlled system (2).

Then, the derivative \( \dot{V} \) is given by

\[
\dot{V} = x\dot{x} + y\dot{y} + z\dot{z} + \frac{h}{m} v\dot{v} + w\dot{w}
\]

\[
= -(k_1 + a)x^2 - cxy - (k_2 - c)y^2
\]

\[
- (k_3 + b)x^2 - k_4 \frac{h}{m} v^2 - k_5 w^2
\]

\[
\leq - \left( k_1 + a - \frac{c}{2} \right) x^2 - \left( k_2 - \frac{3}{2} c \right) y^2
\]

\[
- (k_3 + b)x^2 - k_4 \frac{h}{m} v^2 - k_5 w^2.
\]

For \( \dot{V} < 0 \), the parameters \( k_1, k_2, k_3, k_4 \) and \( k_5 \) should satisfy that
\( k_1 + a - \frac{c}{2} > 0, \quad k_1 > \frac{c}{2} - a, \quad k_1 = 0, \)
\( k_1 - \frac{c}{2} > 0, \quad k_1 > \frac{c}{2}, \quad k_1 = 30, \)
\( k_1 + b > 0, \quad k_1 > \frac{c}{2}, \quad k_1 = 0, \)
\( k_1 > 0, \quad k_1 = 1, \)
\( m/k > 0, \quad k > 0, \quad k_1 = 1. \)

From Theorem 1, the controlled system (2) is globally asymptotically stable at the origin. Thus, the controller \( u_c \) can be designed as
\[
\begin{align*}
\mathbf{u}_c &= \begin{bmatrix} u_{1c} & u_{2c} & u_{3c} & u_{4c} & u_{5c} \end{bmatrix}^T \\
&= \begin{bmatrix} 0 & -30y & 0 & -v & -w \end{bmatrix}^T
\end{align*}
\] (5)

3.3. Numerical Simulation under the Controller \( u_c \)

The curves of the state variables of the controlled system (2) before and after adding the controller \( u_c \) are shown in Figures 2 and 3 respectively. Comparing Figure 3 with Figure 2, it can be found that

Figure 2  Curves of the state variables before adding \( u_c \).

Figure 3  Curves of the state variables after adding \( u_c \).

the state variables \( x, y, z, v \) and \( w \) converge to zero asymptotically and rapidly. Meanwhile, the Lyapunov exponents of the controlled system (2) are \( \lambda_{c_1} = -1.0321, \lambda_{c_2} = -1.0327, \lambda_{c_3} = -3.0000, \lambda_{c_4} = -17.4666 \) and \( \lambda_{c_5} = -17.4687 \), which are all negative. It implies that the controlled system (2) is no longer hyperchaotic but asymptotically stable at the origin. It illustrates that the linear feedback controller \( u_c \) is feasible and effective for hyperchaos control of the 5D system (2).

3.4. Simplification of the Controller \( u_c \)

Corollary 1. Let \( x = 0 \) be an equilibrium point for \( \dot{x} = f(x) \), where \( f: D \to \mathbb{R}^5 \) is a locally Lipschitz map from a domain \( D \subset \mathbb{R}^5 \) into \( \mathbb{R}^5 \). Let \( V: \mathbb{R}^5 \to \mathbb{R} \) be a continuously differentiable, radially unbounded, positive definite function such that \( V(x) \leq 0 \) for all \( x \in \mathbb{R}^5 \). Let \( S = \{ x \in \mathbb{R}^5 | V(x) = 0 \} \) and suppose that no solution can stay identically in \( S \), other than the trivial solution \( x(t) = 0 \). Then, the origin is globally asymptotically stable [4].

Assume that the minimum number of the feedback variables might be equal to the number of the positive Lyapunov exponents [5]. The 5D hyperchaotic system (1) has two positive Lyapunov exponents, but there are three feedback variables in Equation (5). Still take Equation (3) as a Lyapunov function candidate for the controlled system (2). Now let \( \dot{k}_1 = 0 \) and substitute \( \dot{k}_2 = \dot{k}_3 = \dot{k}_4 = 0 \) into Equation (4). Then, the derivative \( \dot{V} \) is reduced to
\[
\dot{V} = xx + y\dot{y} + zz + \frac{h}{m} y\dot{y} + w\dot{w}
\]
\[
= -ax^2 + cxy - (k_2 - \frac{3}{2})y^2 - bz^2 - k_3w^2
\]
\[
\leq -\left( a - \frac{c}{2} \right) x^2 - \left( k_2 - \frac{3}{2} \right) y^2 - bz^2 - k_3w^2.
\]

For \( \dot{V} \leq 0 \), the parameters \( k_2 \) and \( k_3 \) should satisfy that
\[
k_2 - \frac{3}{2} > 0, \quad k_2 > \frac{3}{2}, \quad k_3 = 30, \quad k_3 = 1.
\]

From Corollary 1, to find \( S = \{ x \in \mathbb{R}^5 | \dot{V}(x) = 0 \} \), note that
\[
\dot{V} = 0 \implies x = y = z = w = 0
\]

Hence, \( S = \{ x \in \mathbb{R}^5 | x = y = z = w = 0 \} \).

Let \( x(t) \) be a solution that belongs identically to \( S = \{ x \in \mathbb{R}^5 | x = y = z = w = 0 \} \), so that
\[
x(t) = y(t) = z(t) = w(t) \equiv 0
\]
\[
\implies x(t) = y(t) = z(t) = \dot{v}(t) = \ddot{w}(t) \equiv 0
\]
\[
\implies v(t) \equiv 0
\]

Therefore, the only solution that can stay identically in \( S = \{ x \in \mathbb{R}^5 | \dot{V}(x) = 0 \} \) is the trivial solution \( x(t) = 0 \). Thus, the origin is globally asymptotically stable. Finally, the controller \( u_c \) in Equation (5) is simplified as
\[
\begin{align*}
\mathbf{u}_c &= \begin{bmatrix} u_{1c} & u_{2c} & u_{3c} & u_{4c} & u_{5c} \end{bmatrix}^T \\
&= \begin{bmatrix} 0 & -30y & 0 & -v & -w \end{bmatrix}^T.
\end{align*}
\] (7)
3.5. Numerical Simulation under the Simplified Controller $u_{cs}$

Let the initial values still be $(x_0, y_0, z_0, v_0, w_0) = (1, 1, 1, 1, 1)$, then the curves of the state variables of the controlled system (2) before and after adding the simplified controller $u_{cs}$ are shown in Figures 2 and 4 respectively. Comparing Figure 4 with Figure 2, it can be found that the state variables $x$, $y$, $z$, $v$, and $w$ converge to zero asymptotically and rapidly. Meanwhile, the Lyapunov exponents of the controlled system (2) are $\lambda_{cs1} = -0.53246$, $\lambda_{cs2} = -0.53248$, $\lambda_{cs3} = -3.0000$, $\lambda_{cs4} = -17.4664$ and $\lambda_{cs5} = -17.4687$, which are all negative. It implies that the controlled system (2) is no longer hyperchaotic but asymptotically stable at the origin. It illustrates that the simplified linear feedback controller $u_{cs}$ is also feasible and effective for hyperchaos control of the 5D system (2). Furthermore, the simplified controller $u_{cs}$ only has two feedback variables, such that it is easier to implement via circuit than the controller $u_{c}$.

4. CONCLUSION

In this paper, a novel 5D hyperchaotic system is reviewed. For hyperchaos control of the 5D system, a linear feedback controller and its simplification are designed via the Lyapunov stability theory. The numerical simulation results demonstrate the validity of the controllers. The study in this paper has some engineering significance.

CONFLICTS OF INTEREST

The author declares no conflicts of interest.

REFERENCES


AUTHOR INTRODUCTION

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