Robust chaos suppression of uncertain unified chaotic systems based on chattering-free sliding mode control

Chih-Hsueh Lin, Chia-Wei Ho, Guo-Hsin Hu, Baswanth Sreeramaneni and Jun-Juh Yan

Abstract
For continuous sliding mode control (SMC) in the unified chaotic systems subjected to matched/unmatched uncertainties, a novel chattering-free SMC design is proposed. First, an augmented state is introduced such that it becomes possible to develop a continuous controller to eliminate the undesired chattering which often appears in the typical SMC. Then by using this chattering-free controller, the chaos behavior in unified chaotic systems with matched uncertainties can be completely suppressed. As for the unmatched uncertainties, every state of controlled systems can be driven and limited to a predictable bound, which is not addressed in the literature. Finally, the effectiveness of the proposed chattering-free controller is verified by the numerical simulations.

Keywords
Unified chaotic systems, matched/unmatched uncertainties, chattering, sliding mode control

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Introduction
Chaos has been found in the dynamics of various engineering fields since the famous Lorenz model was proposed to describe the dynamics of the atmosphere. The chaotic response looks random, but it is quite different from the stochastic process. Unlike stochastic processes, chaotic systems are with deterministic nonlinear dynamics to illustrate the chaotic behavior. And there are many distinct characteristics, such as positive largest Lyapunov exponents, boundedness of strange attractors, initial value sensitivity (so-called butterfly effect), extensive spectrums of Fourier transform, random-like responses, fractal properties of states, and so forth. Because chaotic phenomena have been discovered in engineering systems and their random-like state response also provides wide applications for communication encryption, many scholars have devoted themselves to the research of chaos control and synchronization. Furthermore, because state responses of chaotic systems are highly sensitive to initial conditions and unpredictable, chaos control has become an important issue in chaos applications. There has been a wide range of effective approaches developed in the literature to control and stabilize the chaotic behavior of systems, for example, robust sliding mode control, feedback control method, backstepping control design, optimal control, and so on. In the above researches, the sliding mode control has received much attention mainly due to the attractive advantages, such as fast and good transient response, simple structure, easy implementation, and good robustness to external disturbances and parameter uncertainties. However, the use of the discontinuous function in SMC causes the chattering phenomenon which can result in high-frequency oscillations and affect the performance in the controlled system. To solve the chattering problem, Zhang proposed an integral SMC method for a class of uncertain chaotic systems to eliminate the undesired chattering. But it needed multi-dimensional inputs to complete the control design, which increases the complexity of the system.

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Another approach frequently introduced to suppress the chattering is to modify the designed discontinuous SMC with the boundary layer method.\textsuperscript{15-16} But it can only ensure the sliding motion outside a specified boundary layer, which will affect the control performance. Also, in the recent works,\textsuperscript{19-21} the adaptive backstepping SMC was proposed to effectively eliminate the chattering and complete the actual engineering system control. However, their methods only developed for matched uncertainties and cannot directly apply to unmatched cases.

In 2002, to bridge the Lorentz attractor with the Chen attractor and the Lü system, the authors\textsuperscript{22} proposed a unified chaotic system which attracted the interest of many scholars. The robust stabilization of unified chaotic systems was considered using sliding mode control theory.\textsuperscript{23-24} The authors\textsuperscript{25} studied the chaos suppression of unified chaotic systems with feedback control. However, the control approaches mentioned\textsuperscript{22-24} are not suitable for systems subjected to external unmatched uncertainties. Usually, external disturbances in control realization are undesired, but due to environmental limitations, it is always inevitable. If external disturbances are not considered in the control design, it will lead to the failure of controlled systems. Usually, when the system is disturbed by unmatched uncertainties, it is impossible to completely eliminate the influence through the controller. Motivated by the aforementioned works, this paper aims to propose a novel continuous SMC to suppress the chaotic behavior of unified chaotic systems even under matched/unmatched uncertainties. Contrary to the previous works for chaos control with SMC, we will introduce an augmented state method to develop a chattering-free SMC design. When the system is interfered with matched uncertainties, its influence can be completely suppressed and the matched uncertainties can also be accurately identified; and when the system is interfered by unmatched uncertainties, although the influence cannot be fully eliminated, every state of controlled systems can be driven and limited to a predictable bound, which is not addressed in the literature.

The rest of this paper is outlined as follows. Notation gives the system and problem formulations including the design of sliding mode control and the switching function. Control performances in the sliding manifold for systems are considered for both matched and unmatched uncertainties. The novel chattering-free SMC is presented in Continuous Chattering-Free Controller Design. Numerical Simulations includes the numerical simulations to evaluate the control performances for both matched/unmatched cases. Finally, conclusions are included in Conclusion.

Notation

\(w^T\) is the transport of a matrix \(w\). \(|w|\) is the Euclidean norm of the vector \(w\). \(I_n\) is the identity matrix with size \(n \times n\). \(\|w\|\) denotes the absolute value of \(w\). \(\text{diag}(\lambda_1,\ldots,\lambda_n) \in \mathbb{R}^{n \times n}\) is a diagonal matrix. \(\text{sign}(x)\) denotes the nonlinear function of \(x\), when \(x > 0, \text{sign}(x) = 1\); when \(x = 0, \text{sign}(x) = 0\); when \(x < 0, \text{sign}(x) = -1\).

System description and problem formulation

A nonlinear unified chaotic system proposed by Lü et al.\textsuperscript{22} is described by

\[
\begin{align*}
\dot{x}_1(t) &= (25\alpha + 10)(x_2(t) - x_1(t)) \\
\dot{x}_2(t) &= (28 - 35\alpha)x_1(t) + (29\alpha - 1)x_2(t) - x_1(t)x_3(t) \\
\dot{x}_3(t) &= x_1(t)x_2(t) - \frac{8 + \alpha}{3}x_3(t)
\end{align*}
\]  

where \(x_i, i = 1, 2, 3\) denote system states and \(\alpha \in [0, 1]\) is the system parameter bridging the Lorentz attractor with the Chen attractor and the Lü attractor. System (1) is with chaotic Lorenz system, original Chen system, and Lü system, respectively, for \(\alpha \in [0, 0.8], \alpha \in (0.8, 1]\) and \(\alpha = 0.8\). Figure 1 shows the strange attractors of the system (1) with \(\alpha = 0.6\) which belongs to the original Chen system.

Problem formulation

By introducing uncertainties and the control input \(u(t)\) for suppressing the chaotic behavior, the controlled system can be expressed by

\[
\begin{align*}
\dot{x}_1(t) &= (25\alpha + 10)(x_2(t) - x_1(t)) + \delta_1(t) \\
\dot{x}_2(t) &= (28 - 35\alpha)x_1(t) + (29\alpha - 1)x_2(t) - x_1(t)x_3(t) + \delta_2(t) + u(t) \\
\dot{x}_3(t) &= x_1(t)x_2(t) - \frac{8 + \alpha}{3}x_3(t) + \delta_3(t)
\end{align*}
\]

where \(\delta_i, i = 1, 2, 3\) are external uncertainties. \(\delta_i, i = 1, 2, 3\) are bounded by \(|\delta_1| \leq \epsilon_1, \epsilon_1 \geq 0\) and \(|\delta_2| \leq \epsilon_2, \epsilon_2 > 0\).

We introduce an augmented state as shown in (3) to the system.

\[
x_u(t) = (28 - 35\alpha)x_1(t) + (29\alpha - 1)x_2(t) - x_1(t)x_3(t) + \delta_2(t) + u(t)
\]

Then by (3), we have

\[
\dot{x}_u(t) = (28 - 35\alpha)x_1(t) + (29\alpha - 1)x_2(t) - x_1(t)x_3(t) + \delta_2(t) + u(t)
\]

For simplicity, we rewrite (4) as

\[
\dot{x}_u(t) = f_1(t) + f_2(t) + \dot{u}(t)
\]

where

\[
f_1(t) = (28 - 35\alpha - x_3(t))((25\alpha + 10)x_2(t) - x_1(t)) + (29\alpha - 1)x_u(t) - x_1^2(t)x_3(t) + \frac{8 + \alpha}{3}x_3(t)
\]

\[
f_2(t) = (28 - 35\alpha - x_3(t))\delta_1(t) - x_1(t)\delta_3(t) + \dot{\delta}_2(t)
\]

Therefore, the augmented state system is obtained as

\[
\begin{align*}
\dot{x}_1(t) &= (25\alpha + 10)(x_2(t) - x_1(t)) + \delta_1(t) \\
\dot{x}_2(t) &= x_u(t) \\
\dot{x}_3(t) &= f_1(t) + f_2(t) + \dot{u}(t) \\
\end{align*}
\]  

\[
\begin{align*}
\dot{x}_1(t) &= x_1(t)x_2(t) - \frac{8 + \alpha}{3}x_3(t) + \delta_3(t)
\end{align*}
\]
This study aims to present a chattering-free SMC to control the chaos behavior in the augmented unified chaotic system (8). By using the SMC technology, we firstly design a proper switching function for the augmented system (8) and ensure the control effect for the system in the sliding manifold even subjected to matched/unmatched uncertainties. Next, we propose a continuous SMC to force the trajectory of the controlled system (8) to hit and stay on the switching surface without chattering. Now define the switching function as

\[ s(t) = x_a(t) + \int_0^t (k_1 x_1(\tau) + k_2 x_2(\tau) + k_3 x_a(\tau)) d\tau \]  

(9)

where \( s(t) \in R, K = [k_1 \ k_2 \ k_3] \in R^{3\times1} \) is a designed gain matrix. If an SMC controller was proposed to guarantee that the controlled system can operate in the sliding manifold (i.e., \( s(t) = s(t) = 0 \)) for \( t \geq t_h, t_h \) is the hitting time for \( s(t) = 0 \), from (9), one has

\[ x_a(t) = -k_1 x_1(t) - k_2 x_2(t) - k_3 x_a(t) \]  

(10)

By (8) and (10), we have

\[
\begin{bmatrix}
\dot{x}_1(t) \\
\dot{x}_2(t) \\
\dot{x}_a(t)
\end{bmatrix} = \begin{bmatrix}
-25\alpha - 10 & 25\alpha + 10 & 0 \\
0 & 0 & 1 \\
-k_1 & -k_2 & -k_3
\end{bmatrix} \begin{bmatrix}
x_1(t) \\
x_2(t) \\
x_a(t)
\end{bmatrix} + \begin{bmatrix}
\delta_1(t) \\
\delta_2(t) \\
\delta_a(t)
\end{bmatrix}
\]

(13)

and we have \( x_1(t) = \phi_1 X(t), x_2(t) = \phi_2 X(t), x_a(t) = \phi_a X(t), \) where \( \phi_i \) denotes the \( i \)-row of \( I_3 \).

We can estimate the bound of \( x_1(t) \), for \( t \geq t_h \) by
\[
|x_1(t)| = |\phi_1 X(t)| \\
\leq |\phi_1 P e^{D(t-h)} P^{-1} X(t_0)| + \|\phi_1 P \int_{t_0}^{t} e^{D(t-\tau)} d\tau P^{-1} \|_{\max} \|\delta(t)\| \\
\leq |\phi_1 P e^{D(t-h)} P^{-1} X(t_0)| \\
+ \|\phi_1 P \text{diag} \left( \frac{e^{D(t-h)}}{\lambda_1} \frac{e^{D(t-h)}}{\lambda_2} \frac{e^{D(t-h)}}{\lambda_3} \right) \left( \frac{\tau}{t_0} \right)^{-1} \|\omega_1\| \\
\leq |\phi_1 P e^{D(t-h)} P^{-1} X(t_0)| + \|\phi_1 P \text{diag} \left( \frac{1}{\lambda_1} \frac{1}{\lambda_2} \frac{1}{\lambda_3} \right) \left( \frac{\tau}{t_0} \right)^{-1} \|\omega_1\|
\]
(14)

Since Re(\lambda_i) < 0, i = 1, 2, 3 have been assigned, we have the bound of \(x_1(t)\) as

\[
\sigma_1 = \lim_{t \to \infty} |x_1(t)| \leq \lim_{t \to \infty} |\phi_1 P e^{D(t-h)} P^{-1} X(t_0)| \\
+ \lim_{t \to \infty} \|\phi_1 P \text{diag} \left( \frac{1}{\lambda_1} \frac{1}{\lambda_2} \frac{1}{\lambda_3} \right) \left( \frac{\tau}{t_0} \right)^{-1} \|\omega_1\|
\]
(15)

Similar to the derivation in (14) and (15), we have

\[
\sigma_2 = \lim_{t \to \infty} |x_2(t)| \leq \|\phi_2 P \text{diag} \left( \frac{1}{\lambda_1} \frac{1}{\lambda_2} \frac{1}{\lambda_3} \right) \left( \frac{\tau}{t_0} \right)^{-1} \|\omega_1\| \\
\sigma_3 = \lim_{t \to \infty} |x_3(t)| \leq \|\phi_3 P \text{diag} \left( \frac{1}{\lambda_1} \frac{1}{\lambda_2} \frac{1}{\lambda_3} \right) \left( \frac{\tau}{t_0} \right)^{-1} \|\omega_1\|
\]
(16)
(17)

Furthermore, from (2), since 0 \leq \alpha \leq 1, we can calculate \(\sigma_4 = \lim_{t \to \infty} |x_4(t)|\) by

\[
\sigma_4 = \lim_{t \to \infty} |x_4(t)| \leq \lim_{t \to \infty} e^{-\alpha t} |x_4(0)| + \lim_{t \to \infty} \left|\frac{3}{8 + \alpha} \omega_2 \right| \\
|\delta(t)| |x_2(t)| \leq \left( \frac{3}{8 + \alpha} \omega_2 + \sigma_1 \sigma_2 \right)
\]
(18)

**Remark 1.** For the system with matched uncertainties (\(\delta(t) = \delta(t) = 0\)), from (15)-(18), it is observed that for the system (8) operating in the sliding manifold (s(t) = 0), we have the bounds \(\sigma_i = 0, i = 1, 2, 3, 4\). It means that all states of controlled systems can be driven and converged to zero even with the matched uncertainty.

**Remark 2.** For the matched uncertainties, since all states including the augmented state \(x_a(t)\) can be suppressed to zero, from (3), we have \(x_a(t) = (28 - 35\alpha)x_1(t) + (29\alpha - 1)x_2(t) - x_1(t)x_3(t) + \delta_2(t) + u(t) = 0\) and the matched uncertainties can also be accurately identified by \(\delta_2(t) = -u(t)\).

**Remark 3.** From (3), the augmented state \(x_a(t)\) includes the matched uncertainty \(\delta_2(t)\), which normally can’t be measured. Therefore, when realizing the proposed switching function in (9) and the continuous SMC controllers in (19) and (20), one can use the relation of \(x_a(t) = \xi(t)\) in (8) to obtain \(x_a(t)\) without using the unmeasurable information of \(\delta_2(t)\).

**Continuous chattering-free controller design**

To achieve the reaching condition \(s(t)\dot{s}(t) < 0\), the continuous SMC is proposed as

\[
\ddot{u}(t) = -f_1(t) + k_1 x_1(t) + k_2 x_2(t) + k_3 x_3(t) + \zeta \eta(t) \text{sign}(s(t))
\]
(19)

or

\[
u(t) = u(t) - \int_{0}^{t} f_1(t) + k_1 x_1(t) + k_2 x_2(t) + k_3 x_3(t) + \zeta \eta(t) \text{sign}(s(t)) dt
\]
(20)

where \(u_0\) is the initial condition of \(u(t)\) and \(\eta(t) = \left| 28 - 35\alpha - x_1(t) \right| \omega_1 + \left| x_1(t) \right| \omega_3 + \rho; \quad \zeta > 1\)
(21)

Substituting (9) and continuous SMC (19) into \(s(t)\dot{s}(t)\), it yields

\[
s(t)\dot{s}(t) = s(t) \left( \dot{x}_4(t) + k_1 x_1(t) + k_2 x_2(t) + k_3 x_3(t) \right)
\]
(22)

Since

\[
|f_2(t)| = \left| 28 - 35\alpha - x_3(t) \right| \delta_1(t) + \left| x_1(t) \right| \delta_3(t) + \left| \dot{x}_2(t) \right|
\]
(23)

one has

\[
s(t)\dot{s}(t) \leq (1 - \zeta) \eta(t) |s(t)|
\]
(24)

Furthermore, since \(\zeta > 1\) is chosen and \(\eta(t) > 0\), it is ensured that \(s(t)\dot{s}(t) \leq 0\). Therefore, \(s(t)\) always converges to zero.

**Remark 4.** The continuous chattering-free SMC design can be systematized as following steps.

**Step 1.** Introduce an augmented state as (3).
Step 2. Choose a matrix $K$ to guarantee that matrix $(A - BK)$ in (11) is with different eigenvalues $\lambda_i$ and $\text{Re}(\lambda_i) < 0, i = 1, 2, 3$.

Step 3. Define the switching function $s(t)$ as (9).

Step 4. Calculate the corresponding eigenvectors for eigenvalues $\lambda_i$ and obtain the invertible matrix $P$.

Step 5. Utilize (15)–(18) to estimate the bounds of $\sigma_i, i = 1, 2, 3, 4$.

Step 6. Construct the continuous chattering-free SMC by using (19) or (20).

**Numerical Simulations**

Consider the nonlinear unified chaotic system described in (2) with $\alpha = 0$ which belongs to the original Lorenz system. According to Step1 in Remark 4, we introduce an augmented state as

$$x_u(t) = 28x_1(t) - x_2(t) - x_3(t)x_1(t) + \delta_2(t) + u(t)$$

Therefore, by (11), we have

$$A = \begin{bmatrix} -10 & 10 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}; B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

(26)

Obviously $(A, B)$ is controllable and by Step2 in Remark 4, we choose $K = [-0.8 \ 44 \ 13]$ and we have...
$\lambda_1 = -9, \lambda_2 = -8, \lambda_3 = -6$. According to Steps 3 and 4, define the switching function $s(t)$ as

$$s(t) = x_a(t) + \int_0^t (-0.8x_1(\tau) + 44x_2(\tau) + 13x_3(\tau))d\tau$$

and construct the invertible matrix

$$P = \begin{bmatrix} -0.7412 & -0.5270 & -0.3801 \\ -0.0741 & -0.1054 & -0.1521 \\ 0.6671 & 0.8433 & 0.9123 \end{bmatrix}$$

The chattering-free SMC $u(t)$ is obtained as (19) or (20) with $\zeta = 2$.

In the following, we consider the matched and unmatched uncertainties, respectively, to perform the simulations and evaluate the present chattering-free SMC design.

**Complete suppression for the matched uncertainty**

In this simulation, we first consider the matched case and the unmatched uncertainties are all zero, i.e., $\delta_1(t) = \delta_3(t) = 0$ and $\delta_2(t) = 0.6 \cos(6t)$ is given as the matched uncertainty. According to Remark 1, we can conclude that the chaotic behavior will be completely suppressed and controlled states can exactly be driven to zero. Meanwhile, the matched uncertainties can be accurately identified by $\delta_2(t) = -u(t) = 0.6 \cos(6t)$. Figures 2, 3, 4 and 5 show the numerical experiments with the initial condition.
According to Steps 3 and 4, define the switching function \( s(t) \) as

\[
s(t) = x_a(t) + \int_0^t (\delta_0 \cdot 44 x_1(\tau) + 13 x_2(\tau) + x_a(\tau)) \, d\tau
\]

The chattering-free SMC \( u(t) \) is obtained as (19) or (20) with \( \xi = 2 \).

In the following, we consider the matched and unmatched uncertainties, respectively, to perform the simulations and evaluate the present chattering-free SMC design.

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Figures 2, 3, 4 and 5 show the numerical experiments with the initial condition

Figure 6. Time responses of original states and augmented state with mismatched uncertainties.

Figure 7. The suppressed states and estimated bounds.

Figure 8. (a) Time response of \( s(t) \), (b) the continuous SMC.
\((x_1(0), x_2(0), x_3(0)) = (0.5, -1.2)\). Figure 2 shows the completely suppressed states and augmented state responses under the proposed controller (20). Figures 3(a) and (b), respectively, show the switching function \(s(t)\) for the uncertain Lorenz system and the continuous control input. Figure 4 shows the response of \(\delta_2(t) + u(t) = 0.6 \cos(6t) + u(t)\). By surveying the simulation results, it observes that the trajectory of the controlled system hits \(s(t) = 0\) without chattering and the controlled states all converge to zero, i.e., the chaotic behavior is completely suppressed as expected. Furthermore, from Figure 4, the value of \(\delta_2(t) + u(t)\) converges to zero which means that the matched uncertainty can be accurately estimated by \(\delta_2(t) = -u(t) = 0.6 \cos(6t)\).

**Conclusion**

In this paper, we propose chaos suppression of unified chaotic systems with robust chattering-free sliding mode control. In contrast to the traditional sliding mode control, an augmented state is introduced such that a continuous control input is newly proposed to eliminate the chattering phenomenon. Then by using this chattering-free controller, the chaos behavior in unified chaotic systems with matched uncertainties can be completely suppressed and the matched uncertainties can also be accurately identified. Moreover, the bounds of controlled states have been evaluated even subjected to mismatched uncertainties. Numerical simulations for both matched and unmatched cases have been performed to verify the effectiveness of this proposed chattering-free SMC method. However, since this proposed design only introduces a single input, the transient process of chaos suppression is longer. Therefore, if one needs significantly speed up the chaos suppression, multi-dimensional inputs are necessary, but they will increase the complexity of the controlled systems. Therefore, in the near future, extending the proposed chattering-free design to obtain the finite-time chaos suppression is the proposed main work.

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