Control of Stochastic Nonlinear Switched Systems using Fuzzy Law

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Abstract. The problem about controller design for stochastic nonlinear switched systems with delay is considered. Stochastic switched nonlinear system is a kind of nonlinear system which integrates switching and nonlinear fuzzy characteristics and can fully reflect stochastic factors. First, the mathematical model of stochastic nonlinear switched systems with time delay and disturbance is given. Second, the corresponding controller is designed for the proposed model. Then, we use the multi-Lyapunov method to establish the closed-loop system on the basis of our designed controller, and give the necessary and sufficient conditions for the stability of the system. The switching law is designed to ensure the stability of subsystems activated by switching time. Finally, through the simulation software, we can see that the stability condition we obtained can make the studied system stable.

1. Introduction

The switched system with special characteristics is an important hybrid system. They stood out very much in the past decades because many physical systems can use this multi-mode system for mathematical modeling. Considering the wide application of switching power supply, the research on switching system has never stopped and some good results have been achieved [1-5].

On the other hand, complex control systems are often encountered in real life. The most basic problem of complex control system is that the system model is too complex to be precisely obtained, so researchers often simplify the system model. In the past decades, the complex system composed of fuzzy thoughts led to the attention of many scholars [6, 7]. The system of T-S is to approximate the non-linear model to multiple linear models in different state space regions, and then uses the non-linear fuzzy membership function to accumulate these linear models.

With the continuous development of computer technology, fuzzy control algorithm came into being, and successfully applied to the control process of the actual industrial system, which has achieved remarkable application effect. In reference [8], Japanese scholars K. Takagi and Sugeno used T-S model to establish equations and control nonlinear systems. For the first time in history, the criterion of stability performance of fuzzy control system is given, which lays the foundation for the development of fuzzy Takagi Sugeno (T-S) model. At the same time, the definition of T-S model is proposed for the first time [9], which is also called type III fuzzy model [10], and is actually a kind of fuzzy dynamic model [11]. The feature of the system is to linearize each sub model, and then connect each linear sub model with fuzzy membership function to get the whole fuzzy nonlinear system.

One of the bridge of communication between system and fuzzy linear system is T-S fuzzy dynamic model, the system makes the fuzzy system has been greatly enriched, the research methods of
nonlinear systems can be used to study the stability of linear system theory, the research literature [12-17] based on this kind of system has a representative, and has been in real life problems a lot has been applied to obtain considerable social and economic benefits.

Stochastic system is a system containing a large number of different stochastic variables [18-20]. It contains internal stochastic parameters, component errors, noise generated during operation and external stochastic interference. The reason for the uncertainty in the system is caused by the existence of stochastic and complex system factors leading to uncertainty is substantial and cannot be avoided. Without considering the stochastic factors existing in the system, there is not very good that originally intended of the design requirements is achieved. For the increase of the time variable, stochastic deviation will not reach the design target of ideal [19]. The fuzzy switching system and stochastic control theory have been greatly developed in their respective fields [20].

Here, we hope to design the corresponding controller and the appropriate switching law, so that the switched fuzzy stochastic input-time delay system is stable.

2. Stochastic Nonlinear Switched System Model(SNSS) With Input Delays

A stochastic switched nonlinear model with multiple time-delay by fuzzy method is considered

\[ R_{i}(t): \text{if } X_{1} \text{ is } \Omega_{i1} \text{ and } \ldots \text{ and } X_{n} \text{ is } \Omega_{i,n} \text{ then} \]

\[ dx(t) = [A_{i1,0} x(t) + A_{i2,0} x(t-\tau) + B_{i1,0} u_{i}(t-\tau) + F_{i1,0} f(t(t))]dt + D_{i1,0} x(t) d\omega(t) \]  

(1)

\[ x_{\delta}(\theta) = \varphi(\theta), \theta \in [-r,0], \delta = 1 \ldots \Theta_{\Gamma(i)}, \text{ with } \Gamma(t) \text{ is the switching law that we are going to design.} \]

\[ A_{i1,0}, A_{i2,0}, B_{i1,0}, F_{i1,0} \text{ and } D_{i1,0} \text{ are all suitable for (1) corresponding matrix. } R_{i}(t) \text{ are the fuzzy inference rule, } M_{\Gamma(i)} \text{ are the number of fuzzy rules, } X = [X_{1}, X_{2}, \ldots X_{n}] \text{ denotes the premise variables vector. For given } \tau > 0. \]

\[ f_{i1,0}(t) \not= f_{i2,0}(x(t), x(t-\tau)) \text{ denote nonlinear known functions.} \]

Assumption: There is an appropriate dimension real matrix \( \Phi \) and \( \Delta \) such that

\[ \left\| f(\tilde{c}(t), \tilde{c}(t-\tau) - f(\kappa, \kappa(t-\tau))\right\| \leq \left\| \Phi(\tilde{c}(t) - \kappa(t))\right\| + \left\| \Delta(\tilde{c}(t-\tau) - \kappa(t-\tau))\right\| \]  

(2)

The mathematical model about the i-th SNSS subsystem can be expressed as

\[ R_{i}: \text{if } X_{1} \text{ is } \Omega_{i1} \text{ and } \ldots \text{ and } X_{n} \text{ is } \Omega_{i,n} \text{ then} \]

\[ dx(t) = [A_{i1,0} x(t) + A_{i2,0} x(t-\tau) + B_{i1,0} u_{i}(t-\tau) + F_{i1,0} f(t(t))]dt + D_{i1,0} x(t) d\omega(t) \]

\[ \delta = 1,2 \ldots \Theta_{\Gamma}, i = 1,2 \ldots \beta . \]  

(3)

So the global model of the i-th SNSS can be expressed as

\[ dx(t) = \sum_{\beta=1}^{\beta} \psi_{i,\beta} \left\{ [A_{i,\beta} x(t) + A_{i2,0} x(t-\tau) + B_{i1,0} u_{i}(t-\tau) + F_{i1,0} f(t(t))]dt + D_{i1,0} x(t) d\omega(t) \right\} \]

(4)

along with

\[ 0 \leq \psi_{i,\beta}(X(t)) \leq 1, \sum_{\beta=1}^{\beta} \psi_{i,\beta} = 1 . \]

(5)

Where

\[ \Xi_{i,\beta}(X(t)) = \prod_{\rho=1}^{\rho} \Omega_{\beta,\rho}(X_{\rho}(t)) \], \( \psi_{i,\beta}(X(t)) = \frac{Y_{i,\beta}(X(t))}{\sum_{\beta=1}^{\beta} Y_{i,\beta}(X(t))} . \]

(6)

\[ \Omega_{\beta,\rho}(X_{\rho}(t)) \text{ represent the membership function that } X_{\rho}(t) \text{ belongs to the fuzzy set } \Omega_{\rho,\beta} . \]

The global control is

\[ u_{i}(t) = \sum_{\beta=1}^{\beta} \psi_{i,\beta} K_{i,\beta} x(t) . \]

(7)

According to equation (7), we can get the global SNSS model
Consider choosing Lyapunov function
\[ V(x) = x^T (t) P x(t) + \int_{t-\tau}^{t} x^T (s) Q x(s) ds + \int_{t-\tau}^{t} x^T (s) Q_r x(s) ds \]
where both \( P \) and \( Q_r, Q \) are positive definite matrices.

Theorem 1. If there are constants \( \Im_{\nu} \) (non negative or non positive) and positive definite symmetric matrix \( P_r, Q_r, Q \), then the system (1) will be asymptotically stable by the following controller (7).

\[
\begin{bmatrix}
\Lambda_i A_{i\delta}^T + A_{i\delta} \Lambda_i + \sum_{j=1}^{\beta} \Im_{\nu} (\Lambda_i - \Lambda_j) \\
\Lambda_i & \gamma_i (D_{i\delta} + D_{i\delta})^T & F_{i\delta} & A_{i\delta} + B_{i\delta} K_{i\delta}
\end{bmatrix}
\]

\[
\begin{pmatrix}
\Lambda_i & -Q_{i\delta} - Q_r + 2 \varepsilon \Phi_i^T \Phi_i & 0 & 0 \\
(D_{i\delta} + D_{i\delta})^T \Lambda_i & 0 & -4 \Lambda_i & 0 \\
F_{i\delta}^T & 0 & 0 & -\varepsilon I \\
A_{i\delta}^T + K_{i\delta}^T B_{i\delta} & 0 & 0 & -Q_{i\delta} - Q_r + 2 \varepsilon \Delta_i^T \Delta_i
\end{pmatrix}
\]

Taking \( \Lambda_i = P_i^{-1} \). We plan switching law
\[ \Gamma(t) = i \in \{1, 2, \ldots, \beta\} \]

Proof: When \( \Im_{\nu} \geq 0 \). For any \( i \in \{1, 2, \ldots, \beta\} \), if \( x^T (t)(\Lambda_i - \Lambda_j)x(t) \geq 0 \), \( \forall \, \nu \in \{1, 2, \ldots, \beta\} \). From (10),

\[
\begin{bmatrix}
A_{i\delta} \Lambda_i + \Lambda_i A_{i\delta}^T & \Lambda_i & \Lambda_i D_{i\delta} + \Lambda_i D_{i\delta}^T & F_{i\delta} & A_{i\delta} + B_{i\delta} K_{i\delta}
\end{bmatrix}
\]

\[
\begin{pmatrix}
\Lambda_i & -Q_{i\delta} - Q_r + 2 \varepsilon \Phi_i^T \Phi_i & 0 & 0 \\
(D_{i\delta} + D_{i\delta})^T \Lambda_i & 0 & -4 \Lambda_i & 0 \\
F_{i\delta}^T & 0 & 0 & -\varepsilon I \\
A_{i\delta}^T + K_{i\delta}^T B_{i\delta} & 0 & 0 & -Q_{i\delta} - Q_r + 2 \varepsilon \Delta_i^T \Delta_i
\end{pmatrix}
\]

For arbitrary \( i \in \{1, 2, \ldots, \beta\} \),

\[
\Omega_i = \left\{ x(t) \in R^n \setminus \{0\} \mid x^T (t)(\Lambda_i - \Lambda_j)x(t) \geq 0 \right\}.
\]

Then \( \bigcup_{i=1}^{\beta} \Omega_i = R^n \setminus \{0\} \). Further, let construct the sets \( \Omega_{\beta} = \Omega_{\beta} - \bigcup_{\lambda=1}^{\beta-1} \Omega_{\lambda} \). Obviously, we have

\[
\bigcup_{i=1}^{\beta} \Omega_i = R^n \setminus \{0\}, \quad \text{and} \quad \Omega_i \cap \Omega_{\lambda} = \Phi, \, i \neq \lambda. \]

The partial differential operator of the system is as follows:

\[
LV(x) = \sum_{\beta=1}^{\beta} \psi_{\beta} \sum_{j=1}^{\beta} \psi_{ij} x^T (t) [A_{i\delta}^T P_i + P_i A_{i\delta}] x(t) + 2 \sum_{\beta=1}^{\beta} \psi_{\beta} \sum_{j=1}^{\beta} \psi_{ij} x^T (t) P_{ij} f_i (t) + \sum_{\beta=1}^{\beta} \psi_{\beta} \sum_{j=1}^{\beta} \psi_{ij} x^T (t) P_{ij} A_{i\delta} x(t - \tau)
\]
\begin{align*}
&+ \sum_{\delta=1}^{4} \sum_{i=1}^{4} \sum_{\lambda=1}^{4} \psi_{\delta} \lambda^T (t) P_{\delta} (B_{\delta} K_{\delta}) x(t - \tau) + \sum_{\delta=1}^{4} \sum_{i=1}^{4} \psi_{\delta} \lambda^T (t - \tau) A_{\delta}^T P_{\delta} x(t) + \sum_{\delta=1}^{4} \sum_{i=1}^{4} \psi_{\delta} \lambda^T (t - \tau) (B_{\delta} K_{\delta})^T P_{\delta} x(t) \\
&\quad + \frac{1}{2} \sum_{\delta=1}^{4} \sum_{i=1}^{4} \psi_{\delta} \lambda^T (t) D_{\delta}^T P_{\delta} D_{\delta} x(t) + \lambda^T (t) D_{\delta}^T P_{\delta} D_{\delta} x(t)) - \lambda^T (t - \tau) Q_{\delta} x(t - \tau) + \lambda^T (t) Q_{\delta} x(t) \\
&= -\lambda^T (t - \tau) Q_{\delta} x(t - \tau) + \lambda^T (t) Q_{\delta} x(t)
\end{align*}

Notice from Assumption 1 and for a scalar \( \varepsilon > 0 \)

\[ \sum_{\delta=1}^{4} \sum_{i=1}^{4} \lambda^T (t) [P_{\delta} A_{\delta} + A_{\delta}^T P_{\delta} + \lambda^T (t) Q_{\delta} x(t) + \lambda^T (t) Q_{\delta} x(t)] x(t) + \sum_{\delta=1}^{4} \sum_{i=1}^{4} \lambda^T (t) (P_{\delta} A_{\delta} x(t - \tau) \right]

Thus,

\[ -\lambda^T (t - \tau) Q_{\delta} x(t - \tau) + 2 \varepsilon \lambda^T (t) \Phi \lambda x(t) + 2 \varepsilon \lambda^T (t - \tau) \Delta^T \lambda x(t - \tau) = \lambda^T (t - \tau) Q_{\delta} x(t - \tau)
\]

\[ + \sum_{\delta=1}^{4} \sum_{i=1}^{4} \sum_{\lambda=1}^{4} \psi_{\delta} \lambda^T (t - \tau) (B_{\delta} K_{\delta})^T P_{\delta} x(t) + \sum_{\delta=1}^{4} \sum_{i=1}^{4} \sum_{\lambda=1}^{4} \psi_{\delta} \lambda^T (t - \tau) (P_{\delta} A_{\delta} x(t - \tau) \right]

\[ = \sum_{\delta=1}^{4} \sum_{i=1}^{4} \sum_{\lambda=1}^{4} \lambda^T (t) \left[ x(t) \right]^{T} \left[ Z_{\delta} \left( P_{\delta} A_{\delta} + Q_{\delta} + 2 \varepsilon \lambda^T \Phi \lambda + \varepsilon \lambda^T \Phi^T \Phi \lambda \right) \right] \left[ x(t - \tau) \right]
\]

(14)

where

\[ Z_{\delta} = P_{\delta} A_{\delta} + A_{\delta}^T P_{\delta} + Q_{\delta} + 2 \varepsilon \lambda^T \Phi \lambda + \varepsilon \lambda^T \Phi^T \Phi \lambda + \frac{1}{4} (D_{\delta} A_{\delta} + A_{\delta} D_{\delta})^T P_{\delta} (D_{\delta} + D_{\delta}) \]

When the above formula is set up, the Ito differential formula can be obtained \( dV(x(t)) < 0 \).

Now, we transform the search problem of (14) to the LMI problem. Considering (14) multiplying the matrix \( \text{diag} \left[ P_{\gamma}^{-1}, I, I \right] \) of both sides (14), we can obtain (12).

4. Illustrative Examples and Results

We also consider time delay and disturbance, and the established SNSS is:

\[ R_{11}: \text{if } \xi_{11}(t) \text{ is } \Omega_{11} \text{ then } dx(t) = [A_{11} x(t) + A_{111} x(t - \tau) + B_{11} u(t - \tau) + F_{11} f(t)] \text{d}t + D_{11} x(t) \text{d} \omega(t) \]

\[ R_{12}: \text{if } \xi_{12}(t) \text{ is } \Omega_{12} \text{ then } dx(t) = [A_{12} x(t) + A_{121} x(t - \tau) + B_{12} u(t - \tau) + F_{12} f(t)] \text{d}t + D_{12} x(t) \text{d} \omega(t) \]

\[ R_{21}: \text{if } \xi_{21}(t) \text{ is } \Omega_{21} \text{ then } dx(t) = [A_{21} x(t) + A_{211} x(t - \tau) + B_{21} u(t - \tau) + F_{21} f(t)] \text{d}t + D_{21} x(t) \text{d} \omega(t) \]

\[ R_{22}: \text{if } \xi_{22}(t) \text{ is } \Omega_{22} \text{ then } dx(t) = [A_{22} x(t) + A_{221} x(t - \tau) + B_{22} u(t - \tau) + F_{22} f(t)] \text{d}t + D_{22} x(t) \text{d} \omega(t) \]

Where

\[ A_{11} = \begin{bmatrix} -15 & 2 \\ 2 & -1 \end{bmatrix}, \quad A_{12} = \begin{bmatrix} -15 & 2 \\ 2 & -1 \end{bmatrix}, \quad A_{21} = \begin{bmatrix} -11 & 6 \\ 3 & -2 \end{bmatrix}, \quad A_{22} = \begin{bmatrix} -12 & 4 \\ 4 & -2 \end{bmatrix}, \quad B_{11} = \begin{bmatrix} -1 \\ 0 \end{bmatrix}, \quad B_{12} = \begin{bmatrix} -1 \\ 1 \end{bmatrix}, \quad B_{21} = \begin{bmatrix} -1 \\ 0 \end{bmatrix}, \quad B_{22} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad D_{11} = \begin{bmatrix} 1 & -2 \\ 6 & 4 \end{bmatrix}, \quad D_{12} = \begin{bmatrix} -3 & 2 \\ -1 & 4 \end{bmatrix}, \quad D_{21} = \begin{bmatrix} 3 & 1 \\ 1 & 1 \end{bmatrix}, \quad D_{22} = \begin{bmatrix} -2 & 1 \\ 1 & 1 \end{bmatrix}, \]


The membership functions are as follows:

\[
\psi_{11}(x_2(t)) = 1 - \frac{1}{2 + e^{-x_2(t)}} , \quad \psi_{12}(x_2(t)) = \frac{1}{2 + e^{-x_2(t)}} , \quad \psi_{21}(x_2(t)) = 1 - \frac{1}{2 + e^{-x_2(t)-0.5}} , \quad \psi_{22}(x_2(t)) = \frac{1}{2 + e^{-x_2(t)-0.5}} .
\]

The non-linearities \( f(t) \) in (1) are

\[
f_i(t) = \begin{bmatrix} 0.2x_i(t) + 0.1x_i(t) \\ 0.1x_i(t) \end{bmatrix} \cos t + \begin{bmatrix} 0.2x_i(t-r) + 0.2x_i(t-r) \\ 0.1x_i(t-r) + 0.2x_i(t-r) \end{bmatrix} \cos t , \quad f_i(t) = \begin{bmatrix} 0.2x_i(t) + 0.1x_i(t) \\ 0.1x_i(t) \end{bmatrix} \sin t + \begin{bmatrix} 0.2x_i(t-r) + 0.2x_i(t-r) \\ 0.1x_i(t-r) + 0.2x_i(t-r) \end{bmatrix} \sin t .
\]

Which satisfy Assumption 1 with

\[
\Phi_1 = \Phi_2 = \begin{bmatrix} 0.2 & 0.1 \\ 0.1 & 0 \end{bmatrix} , \quad \Lambda_1 = \Lambda_2 = \begin{bmatrix} 0.2 & 0.1 \\ 0.1 & 0.2 \end{bmatrix} .
\]

Here \( \delta, \lambda = 1, 2 \), \( r = 1 \), \( z_1 = 1 \), by solving LMI, the result is obtained

\[
P_1 = \begin{bmatrix} 0.2156 & 0.1024 \\ 0.1024 & 0.1234 \end{bmatrix} , \quad P_2 = \begin{bmatrix} 0.1245 & -0.0248 \\ -0.0248 & 0.2456 \end{bmatrix} , \quad Q_1 = \begin{bmatrix} 0.2547 & 0.0248 \\ 0.0248 & 0.3487 \end{bmatrix} , \quad Q_2 = \begin{bmatrix} 0.2149 & 0.1548 \\ 0.1548 & 0.1575 \end{bmatrix} ,
\]

\[
Q_{21} = \begin{bmatrix} 0.2487 & 0.1693 \\ 0.1693 & 0.2615 \end{bmatrix} , \quad Q_{22} = \begin{bmatrix} 0.1548 & 0.1956 \\ 0.1956 & 0.5648 \end{bmatrix} , \quad K_{11} = \begin{bmatrix} 0.2458 & 0.5648 \end{bmatrix} , \quad K_{12} = \begin{bmatrix} -1.2466 \\ 2.2456 \end{bmatrix} ,
\]

\[
K_{21} = \begin{bmatrix} 0.3145 \\ 0.3145 \end{bmatrix} , \quad K_{22} = \begin{bmatrix} -2.5489 \\ 1.2642 \end{bmatrix} .
\]

Taking the initial condition of the system \( x(0) = [-10, 14]^T \) as an example, the state curve is shown in Figure 1 and Figure 2. Then the validity of the theorem can be verified.

![Figure 1. State curve of SNSS (1) with delay](image1.png)

![Figure 2. State curve of stochastic fuzzy systems with delay](image2.png)

5. Conclusion

Stability of SNSS with input delay using fuzzy law is studied. The switched fuzzy control system with stochastic factors has good control effect. Based on Lyapunov function method, the stability condition can be given in the form of LMI in solution, and a switching control strategy is proposed when the system has large fluctuation. The ideal stability results can be made to the global switched fuzzy stochastic systems. Finally, the feasibility and effectiveness of the method are verified by simulation experiments.

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