Reduced-order Fuzzy Modeling for Nonlinear Switched Systems

Xiaojie Su¹, Peng Shi², Ligang Wu³, Lixian Zhang³ and Yuxin Zhao⁴

Abstract — In this paper, the problem of model approximation is investigated for T-S fuzzy switched system with stochastic disturbance. For a high-order considered system, our attention is focused on the construction of a reduced-order model, which not only approximates the original system well with a Hankel-norm performance but also translates it into a lower-dimensional linear switched system. By average dwell time approach and the piecewise Lyapunov function technique, a sufficient condition is first proposed to guarantee the mean-square exponential stability with a Hankel-norm error performance for the system. The model approximation is then converted into a convex optimization problem by using a linearization procedure.

I. INTRODUCTION

High-order complex mathematical modeling of physical systems and processes is often encountered in practical applications. It results in serious hardship to analysis and synthesis of the concerning systems. Hence, considerable interests have been attracted to solve the problem of simplifying these models with minimum sacrifice of accuracy. In the past two decades, the issue of model reduction has been paid considerable attention. There are an arm of efficient approaches to settle the difficulty of model reduction, such as the optimal $H_2$ approach [19], the $H_\infty$ approach [14], [18], the $L_2-L_\infty$ approach [6] and the optimal Hankel-norm approach [13]. The model reduction problem with a Hankel-norm sense has been investigated by numerous researchers. The essence of the model reduction problem with a Hankel-norm sense is to find a desired lower-dimension system such that the difference between the original high-dimension system and the desired lower-dimension one satisfies a prescribed Hankel-norm bound constraint [17]. However, for fuzzy switched systems with stochastic disturbance, limited results are reported for the model reduction problem with a Hankel-norm sense, which motivates this research work.

Switched systems form an important class of hybrid systems, which consist of a finite number of subsystems and a switching rule indicating the active subsystem at each instant of time [3], [5]. The subsystems are employed to capture the dominant dynamics of the system in different operation modes, which are represented by differential/differential equations. At a particular time, the subsystem is being activated by the respect switching signal, that is, the system is working in the corresponding operation mode. The study on switched systems has been paid a lot of research attention. For example, the problem of stability analysis and stabilization are studied in [16], sliding mode controller design method is proposed in [7], filtering problem is investigated in [11], optimal control problems are solved in [12], and model reduction is addressed in [19].

On another research front, it is generally known that there has been an effective method with the advent of the T-S fuzzy model [15] on the analysis and synthesis of nonlinear systems. Therefore, researchers have been paying remarkable attention for analyzing and synthesizing the problems of T-S fuzzy systems. So far, a considerable number of results on the analysis and control of T-S fuzzy systems have been reported. To mention a few, the problem of designing controller is investigated in [2], [9]. The problem of filtering is studied in [4], [10], and the problem of $H_\infty$ model reduction is solved in [14]. However, to our knowledge, few results in the literature on model reduction with a Hankel-norm sense for fuzzy switched stochastic systems are available.

II. SYSTEM DESCRIPTION AND PRELIMINARIES

In this paper, we consider a class of nonlinear switched systems with stochastic disturbance which can be described by the following T-S fuzzy switched model with stochastic disturbance:

♦ Plant Form:

Rule $R_i^\gamma$: IF $\theta_1(\beta,t)$ is $\mu_{i1,\beta}(\beta)$ and $\theta_2(\beta,t)$ is $\mu_{i2,\beta}(\beta)$ and ... and $\theta_p(\beta,t)$ is $\mu_{ip,\beta}(\beta)$, THEN

$$\begin{align*}
&dx(t) = [A_1(\beta)x(t) + B_1(\beta)u(t)]dt + E_1(\beta)x(t)d\omega(t), \\
y(t) = C_1(\beta)x(t), & \quad i = 1, 2, \ldots, r,
\end{align*}$$

(1)

where $x(t) \in \mathbb{R}^n$ is the state; $u(t) \in \mathbb{R}^l$ is the input which belongs to $L_2[0,\infty]$; $y(t) \in \mathbb{R}^m$ is the output; $\omega(t)$ is a scalar Brownian motion defined on the probability space $(\Omega, \mathcal{F}, \{\mathcal{F}_t\}_{t \geq 0}, \mathbb{P})$, and it satisfies $E\{d\omega(t)\} = 0$ and $E\{d\omega^2(t)\} = dt$; $r$ is the number of IF-THEN rules, $\mu_{i1}(\beta), \ldots, \mu_{ip}(\beta)$ are the fuzzy sets; $\theta_1(\beta,t), \theta_2(\beta,t), \ldots, \theta_p(\beta,t)$ are the premise variables; $\{(A_i(\beta), B_i(\beta), E_i(\beta), C_i(\beta)) : \beta \in \mathcal{I}\}$ is a family of matrices parameterized by an index set $\mathcal{I} = \{1, 2, \ldots, S\}$ and $\beta : \mathbb{R} \to \mathcal{I}$ is a piecewise constant function of time $t$ called a switching signal. At a given time $t$, the value of $\beta(t)$,
denoted by $\beta$ for simplicity, might depend on $t$ or $x(t)$, or both, or may be generated by any other hybrid scheme. As in [3], we assume that the value of $\beta(t)$ is unknown, but its instantaneous value is available in real time. For each possible value $\beta(t) = j, j \in \mathcal{J}$, we will denote the system matrices associated with mode $j$ by

\[
\begin{align*}
A_i(j) &= A_i(\beta), & B_i(j) &= B_i(\beta), \\
C_i(j) &= C_i(\beta), & E_i(j) &= E_i(\beta),
\end{align*}
\]

where $A_i(j), B_i(j), C_i(j), E_i(j)$ are constant matrices. Corresponding to the switching signal $\beta(t)$, we have the switching sequence $\{ (j_0, t_0), (j_1, t_1), \ldots, (j_k, t_k) \ldots \}$ with $t_0 = 0$, which means that the $j_k$th subsystem is activated when $t \in [t_k, t_{k+1}).$

It is assumed that the premise variables do not depend on the input variables $u(t)$. Given a pair of $(x(t), u(t))$, the final output of the fuzzy switched systems with stochastic disturbance is inferred as follows:

\[
\begin{align*}
\dot{x}(t) &= \sum_{i=1}^{r} h_{i(\beta)}(\theta(\beta, t)) \left\{ [A_i(\beta)x(t) + B_i(\beta)u(t)] dt + E_i(\beta)x(t)d\omega(t) \right\}, \\
y(t) &= \sum_{i=1}^{r} h_{i(\beta)}(\theta(\beta, t)) C_i(\beta)x(t), \quad i = 1, 2, \ldots, r,
\end{align*}
\]

where
\[
\begin{align*}
h_{i(\beta)}(\theta(\beta, t)) &= \nu_{i(\beta)}(\theta(\beta, t)) / \sum_{i=1}^{r} \nu_{i(\beta)}(\theta(\beta, t)), \\
\nu_{i(\beta)}(\theta(\beta, t)) &= \prod_{l=1}^{p} \mu_{i(\beta)}(\theta_l(\beta, t)),
\end{align*}
\]

and $\mu_{i(\beta)}(\theta_l(\beta, t))$ is the grade of membership of $\theta_l(\beta, t) \in \mu_{i(\beta)}$. Suppose $\nu_{i(\beta)}(\theta(\beta, t)) \geq 0, i = 1, 2, \ldots, r, \quad \sum_{i=1}^{r} \nu_{i(\beta)}(\theta(\beta, t)) > 0$ for all $t$. Therefore, $h_{i(\beta)}(\theta(\beta, t)) \geq 0$ for $i = 1, 2, \ldots, r$ and $\sum_{i=1}^{r} h_{i(\beta)}(\theta(\beta, t)) = 1$ for all $t$.

We are interested in approximating system in (2) by a reduced-order switched system represented by:

\[
\begin{align*}
\dot{x}(t) &= \left[ \hat{A}(\beta)\hat{x}(t) + \hat{B}(\beta)u(t) \right] dt + \hat{E}(\beta)\hat{x}(t)d\omega(t), \\
\dot{y}(t) &= C(\beta)\hat{x}(t),
\end{align*}
\]

where $\hat{x}(t) \in \mathbb{R}^k$ is the state of the reduced-order switched system with $k < n$; $\hat{A}(\beta), \hat{B}(\beta), \hat{C}(\beta)$ and $\hat{E}(\beta)$ are appropriately dimensioned matrices to be determined. Augmenting the model in (2) to include the states of system in (3), we obtain the following error system:

\[
\begin{align*}
\dot{x}(t) &= \sum_{i=1}^{r} h_{i(\beta)}(\theta(\beta, t)) \left\{ \left[ A_i(\beta)\hat{x}(t) + B_i(\beta)u(t) \right] dt + E_i(\beta)\hat{x}(t)d\omega(t) \right\}, \\
e(t) &= \sum_{i=1}^{r} h_{i(\beta)}(\theta(\beta, t)) C_i(\beta)\hat{x}(t),
\end{align*}
\]

where $\hat{x}(t) \triangleq [x^T(t) \, \dot{x}^T(t)]^T, e(t) \triangleq y(t) - \hat{y}(t)$ and

\[
\begin{align*}
\tilde{A}_i(\beta) &\triangleq \begin{bmatrix} A_i(\beta) & 0 \\ 0 & \hat{A}(\beta) \end{bmatrix}, & \tilde{E}_i(\beta) &\triangleq \begin{bmatrix} E_i(\beta) & 0 \\ 0 & \hat{E}(\beta) \end{bmatrix}, \\
\tilde{C}_i(\beta) &\triangleq \begin{bmatrix} C_i(\beta) - \hat{C}(\beta) \\ \hat{B}(\beta) \end{bmatrix},
\end{align*}
\]

Before formulating the main problem, we first give the following definitions.

\textbf{Definition 1}: The equilibrium $\hat{x}^*(t) = 0$ of system in (4) with $u(t) = 0$ is said to be mean-square exponentially stable under $\beta(t)$ if its solution $\hat{x}(t)$ satisfies

\[
E \left\{ \|\hat{x}(t)\|^2 \right\} < \eta \|\hat{x}(0)\|^2 e^{-\lambda(t-t_0)}, \quad \forall t \geq t_0,
\]

for constants $\eta \geq 1$ and $\lambda > 0$.

\textbf{Definition 2}: [8] For any $T_2 > T_1 \geq 0$, let $N_{\beta}(T_1, T_2)$ denote the number of switchings of $\beta(t)$ over $(T_1, T_2)$. If $N_{\beta}(T_1, T_2) \leq N_0 + (T_2 - T_1)/T_m$ holds for $T_m > 0, N_0 \geq 0$. Then, $T_m$ is called the average dwell time.

\textbf{Definition 3}: [11] For $\alpha > 0$ and $\gamma > 0$, the system in (4) is said to be mean-square exponentially stable with a Hankel-norm error performance $(\gamma, \alpha)$, if under $\beta(t)$ it is mean-square exponentially stable with $u(t) = 0$, then holds

\[
E \left\{ \int_0^T e^{-\alpha t} e^T(t)u(t)dt \right\} < \gamma \int_0^T u^T(t)u(t)dt, \quad (5)
\]

for all $u(t) \in L_2[0, \infty)$ with $u(t) = 0, \forall t \geq T$.

\textbf{III. HANKEL-NORM PERFORMANCE ANALYSIS}

In this section, we will present the sufficient condition of the mean-square exponential stability and the Hankel-norm error performance for the error system in (4).

\textbf{Theorem 1}: Given scalars $\alpha > 0$ and $\gamma > 0$, suppose there exist matrices $0 < P_j(j) \in \mathbb{R}^{(n+k)x(n+k)}$ and $0 < P_j(j) \in \mathbb{R}^{(n+k)x(n+k)}$ such that for $j \in \mathcal{J}$, $i = 1, 2, \ldots, r,$

\[
\Pi_{ij}(j) \triangleq \begin{bmatrix} \Pi_{11ij}(j) & \Pi_{12ij}(j) & \Pi_{13ij}(j) & \Pi_{14ij}(j) \\
\Pi_{21ij}(j) & \Pi_{22ij}(j) & \Pi_{23ij}(j) & \Pi_{24ij}(j) \\
\Pi_{31ij}(j) & \Pi_{32ij}(j) & \Pi_{33ij}(j) & \Pi_{34ij}(j) \\
\Pi_{41ij}(j) & \Pi_{42ij}(j) & \Pi_{43ij}(j) & \Pi_{44ij}(j) \end{bmatrix} < 0, (6)
\]

where

\[
\Pi_{11ij}(j) \triangleq P_j(j) \tilde{A}_i(j) + \tilde{A}_i^T(j)P_j(j) + \alpha P_j(j), \\
\Pi_{12ij}(j) \triangleq P_j(j) \tilde{A}_i(j) + \tilde{A}_i^T(j)P_j(j) + \alpha P_j(j),
\]

Then, the error system in (4) is mean-square exponentially stable with a Hankel-norm error performance $(\gamma, \alpha)$ for any switching signal with average dwell time satisfying $T_m > T_m = \frac{\ln \mu}{\gamma}$, where $\mu \geq 1$ satisfies

\[
P_j(j) \leq \mu P_j(s), \quad P_j(j) \leq \mu P_j(s), \quad \forall j, s \in \mathcal{J}.
\]

Moreover, an estimate of the state decay is given by

\[
E \left\{ \|\hat{x}(t)\|^2 \right\} \leq \eta e^{-\lambda t} \|\hat{x}(0)\|^2, \quad (10)
\]

where

\[
\lambda = \frac{\alpha - \ln \mu}{T_m} > 0, \quad a = \min_{j \in \mathcal{J}} \lambda_{\min}(P_j(j)), \\
\eta = \frac{b}{a} \geq 1, \quad b = \max_{j \in \mathcal{J}} \lambda_{\max}(P_j(j)).
\]

\textbf{Proof}: Choose a piecewise Lyapunov functional of the following form:

\[
V(\hat{x}_t, \beta, t) \triangleq \hat{x}_t^T(t)P_j(\beta)\hat{x}_t(t), \\
W(\dot{\hat{x}}_t, \beta, t) \triangleq \hat{x}_t^T(t)P_j(\beta)\hat{x}_t(t),
\]

where $P_1(\beta) > 0, P_2(\beta) > 0, \beta \in \mathcal{J}$ are to be determined. Then, along the solution of system in (4) for a fixed $\beta$, by Itô formula and Lyapunov theory, we can obtain the error system in (4) is mean-square exponentially stable.
Moreover, according to (11) and the Hankel norm performance index in definition 2, we have
\[ E \left\{ \int_0^T e^{-\alpha t} e^T(t) e(t) dt \right\} < \gamma^2 \int_0^T u^T(t) u(t) dt, \]
which is the Hankel-norm error performance defined in (5). This completes the proof.

IV. MODEL APPROXIMATION BY THE HANKEL-NORM APPROACH

Now, we will solve the model approximation problem for fuzzy switched stochastic systems. Firstly, we present the following theorem to pave the way to solve the model reduction problem for the concerned systems.

Theorem 2: Given scalars \( \alpha > 0, \gamma > 0 \) and \( 0 < \vartheta \leq 1 \), suppose there exist matrices \( 0 < P(j) \in \mathbb{R}^{(n+k) \times (n+k)} \) such that for \( j \in J, i = 1, 2, \ldots, r \),
\[
\begin{bmatrix}
\tilde{P}_{11}(j) & P(j) \tilde{B}(j) E^T(j) P(j) \\
\ast & -\gamma^2 I \\
\ast & -\gamma^2 I & -P(j)
\end{bmatrix} < 0,
\]
(12)
\[
\begin{bmatrix}
\tilde{P}_{11}(j) & \theta E^T(j) P(j) \right\} < 0,
\]
(13)
where
\[
\tilde{P}_{11}(j) \triangleq P(j) \tilde{A}_i(j) + \tilde{A}_i^T(j) P(j) + \alpha P(j),
\]
\[
\tilde{P}_{11}(j) \triangleq \vartheta P(j) \tilde{A}_i(j) + \vartheta \tilde{A}_i^T(j) P(j) + \vartheta \alpha P(j).
\]
(14)
Then, the error system in (4) is mean-square exponentially stable with a Hankel-norm error performance \((\gamma, \alpha)\) for any switching signal with average dwell time satisfying \( T_a > T^*_a = \frac{\ln \mu}{\alpha} \), where \( \mu \geq 1 \) satisfies \( P(j) \leq \mu P(s), \forall j, s \in J \).

Moreover, an estimate of the state decay is given by
\[ E \left\{ \| \tilde{x}(t) \|^2 \right\} \leq \eta e^{-lt} \| \tilde{x}(0) \|^2, \]
(16)
where
\[ \lambda = \alpha - \frac{\ln \mu}{\gamma} > 0, \quad \alpha = \min_{j \in J} \lambda_{\min}(P(j)) , \]
\[ \eta = \frac{\lambda}{b} \geq 1, \quad b = \max_{j \in J} \lambda_{\max}(P(j)). \]
Proof: According to the same line as the proof of Theorem 1 and \( 0 < \vartheta \leq 1 \), it is easy to testify that the error system (\( \Sigma \)) in (4) is mean-square exponentially stable with a Hankel-norm error performance \((\gamma, \alpha)\) for any switching signal with average dwell time satisfying \( T_a > T^*_a = \frac{\ln \mu}{\alpha} \) if there exists \( P(j) > 0 \) satisfying (12)–(17). Thus, it completes the proof.

In the following, we can obtain the model reduction matrix parameters for fuzzy switched systems with stochastic disturbance.

Theorem 3: Consider the error system (\( \Sigma \)) in (4). For given scalars \( \alpha > 0, \gamma > 0 \) and \( 0 < \vartheta \leq 1 \), suppose there exist matrices \( 0 < P(j) \in \mathbb{R}^{n \times n}, 0 < Q(j) \in \mathbb{R}^{k \times k}, A(j) \in \mathbb{R}^{k \times l}, B(j) \in \mathbb{R}^{k \times k}, C(j) \in \mathbb{R}^{m \times k} \) and \( E(j) \in \mathbb{R}^{k \times k} \) such that for \( j \in J, i = 1, 2, \ldots, r \),
\[
\begin{bmatrix}
\tilde{P}_{11}(j) & \tilde{P}_{12}(j) \tilde{P}_{13}(j) \tilde{P}_{14}(j) \tilde{P}_{15}(j) \\
\ast & \tilde{P}_{22}(j) \tilde{P}_{23}(j) \tilde{P}_{24}(j) \tilde{P}_{25}(j) \\
\ast & \ast & -\gamma^2 I \\
\ast & \ast & -\gamma^2 I & 0 \\
\ast & \ast & \ast & -P(j) \right\} < 0,
\]
(18)
where
\[
\begin{bmatrix}
\tilde{P}_{11}(j) & \tilde{P}_{12}(j) \tilde{P}_{13}(j) \tilde{P}_{14}(j) \tilde{P}_{15}(j) \\
\ast & \tilde{P}_{22}(j) \tilde{P}_{23}(j) \tilde{P}_{24}(j) \tilde{P}_{25}(j) \\
\ast & \ast & -\gamma^2 I \\
\ast & \ast & -\gamma^2 I & 0 \\
\ast & \ast & \ast & -P(j) \right\} < 0,
\]
(19)
where
\[
\begin{bmatrix}
I_{k \times k} \\
0_{(n-k) \times k} \\
I_{k \times k} \\
0_{(n-k) \times k} \\
l_{k \times k} \\
0_{(n-k) \times k}
\end{bmatrix}
\]
(20)
Performing a congruence transformation to (12)–(13) by \( \text{diag}(J(j), I, J(j)) \) and \( \text{diag}(J(j), J(j), I) \) respectively, we obtain
\[
\begin{bmatrix}
\text{diag}(J(j), J(j)) & J^T(j)(23) P(j) \right\} < 0,
\]
(21)
where
\[
\begin{bmatrix}
\tilde{P}_{11}(j) & \tilde{P}_{12}(j) \tilde{P}_{13}(j) \tilde{P}_{14}(j) \tilde{P}_{15}(j) \\
\ast & \tilde{P}_{22}(j) \tilde{P}_{23}(j) \tilde{P}_{24}(j) \tilde{P}_{25}(j) \\
\ast & \ast & -\gamma^2 I \\
\ast & \ast & -\gamma^2 I & 0 \\
\ast & \ast & \ast & -P(j) \right\} < 0,
\]
(22)
where
\[
\begin{bmatrix}
\tilde{P}_{11}(j) & \tilde{P}_{12}(j) \tilde{P}_{13}(j) \tilde{P}_{14}(j) \tilde{P}_{15}(j) \\
\ast & \tilde{P}_{22}(j) \tilde{P}_{23}(j) \tilde{P}_{24}(j) \tilde{P}_{25}(j) \\
\ast & \ast & -\gamma^2 I \\
\ast & \ast & -\gamma^2 I & 0 \\
\ast & \ast & \ast & -P(j) \right\} < 0,
\]
(23)
where
\[
\begin{bmatrix}
\tilde{P}_{11}(j) & \tilde{P}_{12}(j) \tilde{P}_{13}(j) \tilde{P}_{14}(j) \tilde{P}_{15}(j) \\
\ast & \tilde{P}_{22}(j) \tilde{P}_{23}(j) \tilde{P}_{24}(j) \tilde{P}_{25}(j) \\
\ast & \ast & -\gamma^2 I \\
\ast & \ast & -\gamma^2 I & 0 \\
\ast & \ast & \ast & -P(j) \right\} < 0,
\]
(24)
\[
\begin{bmatrix}
J^T(j)\Phi_11(j)\bar{J}(j) & \partial J^T(j)\overline{E}^T(j)P(j)\bar{J}(j) \\
\ast & -\partial J^T(j)P(j)\bar{J}(j) \\
\ast & \ast
\end{bmatrix}
< 0, \quad (24)
\]

Considering (21)–(22), we have
\[
\begin{align*}
J^T(j)P(j)A(j) &= \begin{bmatrix} P(j)A(j) & \mathcal{H}(A(j)) \end{bmatrix}, \\
J^T(j)\overline{E}^T(j)P(j)\bar{J}(j) &= \begin{bmatrix} E^T(j)P(j) & E^T(j)HQ(j) \end{bmatrix}, \\
J^T(j)P(j)B_i(j) &= \begin{bmatrix} P(j)B_i(j) + \mathcal{H}(B(j)) \end{bmatrix}, \\
J^T(j)P(j)\bar{B}_i(j) &= \begin{bmatrix} P(j)H\bar{B}(j) \end{bmatrix}, \\
J^T(j)\bar{C}^T(j) &= \begin{bmatrix} \bar{C}^T(j) \\
\ast \quad \ast
\end{bmatrix}.
\end{align*}
\]

Considering (25), we can obtain (18)–(19) from (23)–(24), respectively. Moreover, notice that (22) is equivalent to
\[
\begin{bmatrix}
\dot{A}(j) \\
\dot{\hat{B}}(j) \\
\bar{C}(j) \\
\dot{E}(j)
\end{bmatrix} = \begin{bmatrix}
P_4^{-1}(j) & 0 & 0 & 0 \\
0 & I & 0 & 0 \\
0 & 0 & P_4^{-1}(j) & 0 \\
0 & 0 & 0 & \Phi(j)
\end{bmatrix} \begin{bmatrix}
A(j) & B(j) & C(j) & E(j)
\end{bmatrix} \begin{bmatrix}
P_4^{-1}(j)P_3(j) & 0 & 0 & I
\end{bmatrix}.
\]

where \( \Phi(j) \triangleq \left( P_4^{-1}(j)P_3(j) \right)^{-1} Q^{-1}(j) \). Note that the matrices \( \hat{A}(j), \hat{B}(j), \bar{C}(j) \) and \( \dot{E}(j) \) in (3) can be written as (26), which implies that \( P_4^{-1}(j)P_3(j) \) can be viewed as a similarity transformation on the state-space realization of the filter and, as such, has no effect on the filter mapping from \( u \) to \( \hat{y} \). Without loss of generality, we may set \( P_4^{-1}(j)P_3(j) = I \), thus obtain (20). Therefore, the reduced-order system (\( \Sigma \)) in (3) can be constructed by (20). This completes the proof.

V. CONCLUSION

The model approximation problem with a Hankel-norm sense has been investigated for fuzzy switched system with stochastic disturbance. By using the average dwell time approach and the piecewise Lyapunov function technique, a sufficient condition has been proposed to guarantee the mean-square exponential stability with a Hankel-norm error performance for the approximation error system. Then, the corresponding solvability condition for the reduced-order switched models has also been established based on the linearization procedure approach.

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