

Robust \mathcal{H}_∞ State-Feedback Control for Uncertain Fuzzy Markovian Jump Systems: LMI-Based Design

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Abstract—This paper investigates the problem of designing a robust state-feedback controller for a class of uncertain Markovian jump nonlinear systems that guarantees the \mathcal{L}_2 -gain from an exogenous input to a regulated output is less than or equal to a prescribed value. First, we approximate this class of uncertain Markovian jump nonlinear systems by a class of uncertain Takagi-Sugeno fuzzy models with Markovian jumps. Then, based on an LMI approach, LMI-based sufficient conditions for the uncertain Markovian jump nonlinear systems to have an \mathcal{H}_∞ performance are derived. An illustrative example is used to illustrate the effectiveness of the proposed design techniques.

Keywords—Robust \mathcal{H}_∞ ; Fuzzy Control; Markovian Jump Systems; LMI

I. INTRODUCTION

Many physical systems may experience abrupt changes in their structure and parameters, caused by phenomena such as component and interconnection failures, parameters shifting, tracking, and the time required to measure some of the variables at different stages. Such system can be modelled by a hybrid system with two components in the state vector. The first one which varies continuously is referred to be the continuous state of the system and the second one which varies discretely is referred to be the mode of the system. There has been an increasing interest in these types of systems during the last decade, mostly due to the growing use of computers in the control of physical plants but also as a result of the hybrid nature of physical processes. A special class of hybrid systems known as Markovian jump systems has been widely used to model manufacturing systems [1] and communication systems [2]. Although linear Markovian jump systems have been extensively studied [3]-[13], to the best of our knowledge, the control design of nonlinear Markovian jump dynamical systems remains as an open research area. Recently, there has been some attempt in this area. In [14], Hamilton-Jacobi-equation-based sufficient conditions for nonlinear Markovian jump systems to have an \mathcal{H}_∞ performance have been derived. However, until now, it is still very difficult to find a global solution to the HJE either analytically or numerically.

Over the past two decades, there has been rapidly growing interest in application of fuzzy logic to control problem. Researches have been focused on its application to industrial processes and a number of successful results have been reported in the literature. In spite of these successes, there are many basic issues remain to be addressed. One of them is how to achieve

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a systematic design that guarantees closed-loop stability and performance. Recently, a great amount of effort has been devoted to describing a nonlinear system using a Takagi-Sugeno fuzzy model (see [15]-[30]). The Takagi-sugeno fuzzy model represents a nonlinear system by a family of local linear models which smoothly blended together through fuzzy membership functions. Unlike conventional modelling techniques which uses a single model to describe the global behavior of a nonlinear system, fuzzy modelling is essentially a multi-model approach in which simple sub-models (typically linear models) are fuzzily combined to described the global behavior of a nonlinear system. Based on this fuzzy model, a number of systematic model-based fuzzy control design methodologies have been developed.

The aim of this paper is to study the problem of designing robust \mathcal{H}_∞ fuzzy state-feedback controller for a class of uncertain nonlinear systems with Markovian jumps. First, we approximate this class of uncertain nonlinear systems with Markovian jumps by a Takagi-Sugeno fuzzy model with Markovian jumps. Then based on an LMI approach, we develop a technique for designing robust \mathcal{H}_∞ fuzzy state-feedback and output feedback controllers such that the \mathcal{L}_2 -gain of the mapping from the exogenous input noise to the regulated output is less than a prescribed value.

This paper is organized as follows. In Section II, system descriptions and definition are presented. In Section III, based on an LMI approach, we develop a technique for designing robust \mathcal{H}_∞ fuzzy state-feedback controller such that the \mathcal{L}_2 -gain of the mapping from the exogenous input noise to the regulated output is less than a prescribed value for the system described in Section II. The validity of this approach is demonstrated by an example from a literature in Section IV. Finally, conclusions are given in Section V.

II. SYSTEM DESCRIPTIONS AND DEFINITIONS

The class of uncertain nonlinear system with Markovian jumps under consideration is described by the following TS fuzzy model with Markovian jumps:

$$\begin{aligned}
 \dot{x}(t) &= \sum_{i=1}^r \mu_i(\nu(t)) \left[[A_i(\eta(t)) + \Delta A_i(\eta(t))]x(t) \right. \\
 &\quad \left. + [B_{1_i}(\eta(t)) + \Delta B_{1_i}(\eta(t))]w(t) \right. \\
 &\quad \left. + [B_{2_i}(\eta(t)) + \Delta B_{2_i}(\eta(t))]u(t) \right], \quad x(0) = 0, \\
 z(t) &= \sum_{i=1}^r \mu_i(\nu(t)) \left[[C_{1_i}(\eta(t)) + \Delta C_{1_i}(\eta(t))]x(t) \right. \\
 &\quad \left. + [D_{12_i}(\eta(t)) + \Delta D_{12_i}(\eta(t))]u(t) \right] \\
 y(t) &= \sum_{i=1}^r \mu_i(\nu(t)) \left[[C_{2_i}(\eta(t)) + \Delta C_{2_i}(\eta(t))]x(t) \right. \\
 &\quad \left. + [D_{21_i}(\eta(t)) + \Delta D_{21_i}(\eta(t))]w(t) \right]
 \end{aligned} \tag{1}$$

where $\nu(t) = [\nu_1(t) \ \cdots \ \nu_\vartheta(t)]$ is the premise variable that may depend on states in many cases, $\mu_i(\nu(t))$ denote the normalized time-varying fuzzy weighting functions for each rule, ϑ is the number of fuzzy sets, $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the input, $w(t) \in \mathbb{R}^p$ is the disturbance which belongs to $\mathcal{L}_2[0, \infty)$, $y(t) \in \mathbb{R}^\ell$ is the measurement, $z(t) \in \mathbb{R}^s$ is the controlled output, the matrix functions $A_i(\eta(t))$, $B_{1_i}(\eta(t))$, $B_{2_i}(\eta(t))$, $C_{1_i}(\eta(t))$, $C_{2_i}(\eta(t))$, $D_{12_i}(\eta(t))$, $D_{21_i}(\eta(t))$, $\Delta A_i(\eta(t))$, $\Delta B_{1_i}(\eta(t))$, $\Delta B_{2_i}(\eta(t))$, $\Delta C_{1_i}(\eta(t))$, $\Delta C_{2_i}(\eta(t))$, $\Delta D_{12_i}(\eta(t))$ and $\Delta D_{21_i}(\eta(t))$ are of appropriate dimensions. $\{\eta(t)\}$ is a continuous-time discrete-state Markov process taking values in a finite set $\mathcal{S} = \{1, 2, \dots, s\}$ with transition probability matrix $Pr \triangleq \{P_{ik}(t)\}$ given by

$$\begin{aligned} P_{ik}(t) &= Pr(\eta(t + \Delta) = k | \eta(t) = i) \\ &= \begin{cases} \lambda_{ik}\Delta + O(\Delta) & \text{if } i \neq k \\ 1 + \lambda_{ii}\Delta + O(\Delta) & \text{if } i = k \end{cases} \end{aligned} \quad (2)$$

where $\Delta > 0$, and $\lim_{\Delta \rightarrow 0} \frac{O(\Delta)}{\Delta} = 0$. Here $\lambda_{ik} \geq 0$ is the transition rate from mode i (system operating mode) to mode k ($i \neq k$), and

$$\lambda_{ii} = - \sum_{k=1, k \neq i}^s \lambda_{ik}. \quad (3)$$

For the convenience of notations, we let $\mu_i \triangleq \mu_i(\nu(t))$, $\eta = \eta(t)$, and any matrix $M(\mu, i) \triangleq M(\mu, \eta = i)$. The matrix functions $\Delta A_i(\eta)$, $\Delta B_{1_i}(\eta)$, $\Delta B_{2_i}(\eta)$, $\Delta C_{1_i}(\eta)$, $\Delta C_{2_i}(\eta)$, $\Delta D_{12_i}(\eta)$ and $\Delta D_{21_i}(\eta)$ represent the time-varying uncertainties in the system and satisfy the following assumption.

Assumption 1:

$$\begin{aligned} \Delta A_i(\eta) &= F(x(t), \eta, t)H_{1_i}(\eta), \\ \Delta B_{1_i}(\eta) &= F(x(t), \eta, t)H_{2_i}(\eta), \\ \Delta B_{2_i}(\eta) &= F(x(t), \eta, t)H_{3_i}(\eta), \\ \Delta C_{1_i}(\eta) &= F(x(t), \eta, t)H_{4_i}(\eta), \\ \Delta C_{2_i}(\eta) &= F(x(t), \eta, t)H_{5_i}(\eta), \\ \Delta D_{12_i}(\eta) &= F(x(t), \eta, t)H_{6_i}(\eta), \end{aligned}$$

$$\text{and } \Delta D_{21_i}(\eta) = F(x(t), \eta, t)H_{7_i}(\eta)$$

where $H_{j_i}(\eta)$, $j = 1, 2, \dots, 7$ are known matrices which characterize the structure of the uncertainties. Furthermore, there exists a positive function $\rho(\eta)$ such that the following inequality holds:

$$\|F(x(t), \eta, t)\| \leq \rho(\eta). \quad (4)$$

We recall the following definition.

Definition 1: Suppose γ is a given positive number. A system of the form (1) is said to have the \mathcal{L}_2 -gain less than or equal to γ if

$$\mathbf{E} \left[\int_0^{T_f} \{z^T(t)z(t) - \gamma^2 w^T(t)w(t)\} dt \right] \leq 0, \quad x(0) = 0 \quad (5)$$

where $\mathbf{E}[\cdot]$ stands for the mathematical expectation, for all T_f and all $w(t) \in \mathcal{L}_2[0, T_f]$.

Note that for the symmetric block matrices, we use $(*)$ as an ellipsis for terms that are induced by symmetry.

This section provides the LMI-based solutions to the problem of designing a robust \mathcal{H}_∞ fuzzy state-feedback controller that guarantees the \mathcal{L}_2 -gain of the mapping from the exogenous input noise to the regulated output to be less than some prescribed value.

Let us consider a robust \mathcal{H}_∞ fuzzy state-feedback controller of the form

$$u(t) = \sum_{j=1}^r \mu_j K_j(\eta)x(t) \quad (6)$$

where $K_j(\eta)$ is the controller gain, such that the inequality (5) is guaranteed. The state space form of the fuzzy system model (1) with the controller (6) is given by

$$\begin{aligned} \dot{x}(t) &= \sum_{i=1}^r \sum_{j=1}^r \mu_i \mu_j \left[[(A_i(i) + B_{2_i}(i)K_j(i)) \right. \\ &\quad + (\Delta A_i(i) + \Delta B_{2_i}(i)K_j(i))]x(t) \\ &\quad \left. + [B_{1_i}(i) + \Delta B_{1_i}(i)]w(t) \right], \quad x(0) = 0. \end{aligned} \quad (7)$$

The following theorem provides sufficient conditions for the existence of a robust \mathcal{H}_∞ fuzzy state-feedback controller. These sufficient conditions can be derived by the Lyapunov approach.

Theorem 1: Consider the system (1). Given a prescribed \mathcal{H}_∞ performance $\gamma > 0$, then the inequality (5) holds if for $i = 1, 2, \dots, s$, there exist matrices $P(i) = P^T(i)$ and any positive constants $\delta(i)$ such that the following linear matrix inequalities hold:

$$P(i) > 0 \quad (8)$$

$$\Psi_{ii}(i) < 0, \quad i = 1, 2, \dots, r \quad (9)$$

$$\Psi_{ij}(i) + \Psi_{ji}(i) < 0, \quad i < j \leq r \quad (10)$$

where

$$\Psi_{ij}(i) = \begin{pmatrix} \Phi_{ij}(i) & (*)^T & (*)^T & (*)^T \\ \mathcal{R}(i)\tilde{B}_{1_i}^T(i) & -\gamma\mathcal{R}(i) & (*)^T & (*)^T \\ \Upsilon_{ij}(i) & 0 & -\gamma\mathcal{R}(i) & (*)^T \\ \mathcal{Z}^T(i) & 0 & 0 & -\mathcal{P}(i) \end{pmatrix}$$

$$\begin{aligned} \Phi_{ij}(i) &= A_i(i)P(i) + P(i)A_i^T(i) + B_{2_i}(i)Y_j(i) \\ &\quad + Y_j^T(i)B_{2_i}^T(i) + \lambda_{ii}P(i) \end{aligned}$$

$$\Upsilon_{ij}(i) = \tilde{C}_{1_i}(i)P(i) + \tilde{D}_{12_i}(i)Y_j(i)$$

$$\mathcal{R}(i) = \text{diag} \{ \delta(i)I, I, \delta(i)I, I \}$$

$$\mathcal{Z}(i) = \left(\sqrt{\lambda_{i1}}P(i) \ \cdots \ \sqrt{\lambda_{i(i-1)}}P(i) \right.$$

$$\left. \sqrt{\lambda_{i(i+1)}}P(i) \ \cdots \ \sqrt{\lambda_{is}}P(i) \right)$$

$$\mathcal{P}(i) = \text{diag} \{ P(1), \dots, P(i-1), P(i+1), \dots, P(s) \}$$

with

$$\begin{aligned} \tilde{B}_{1i}(z) &= [I \ I \ I \ B_{1i}(z)] \\ \tilde{C}_{1i}(z) &= \left[\begin{array}{c} \gamma\rho(z)H_{1i}^T(z) \ \sqrt{2}\aleph(z)\rho(z)H_{4i}^T(z) \\ 0 \ \sqrt{2}\aleph(z)C_{1i}^T(z) \end{array} \right]^T \\ \tilde{D}_{12i}(z) &= \left[\begin{array}{c} 0 \ \sqrt{2}\aleph(z)\rho(z)H_{6i}^T(z) \\ \gamma\rho(z)H_{3i}^T(z) \ \sqrt{2}\aleph(z)D_{12i}^T(z) \end{array} \right]^T \\ \aleph(z) &= \left(1 + \rho^2(z) \sum_{i=1}^r \sum_{j=1}^r [\|H_{2i}^T(z)H_{2j}(z)\|] \right)^{\frac{1}{2}}. \end{aligned}$$

Furthermore, a suitable choice of the fuzzy controller is

$$u(t) = \sum_{j=1}^r \mu_j K_j(z)x(t) \tag{11}$$

where

$$K_j(z) = Y_j(z)(P(z))^{-1}. \tag{12}$$

Proof: Due to the page limit, the detail of the proof has been omitted. ■

IV. ILLUSTRATIVE EXAMPLE

Consider a modified Samuelson multiplier-accelerator economic model based on [37] which is governed by the following difference equations:

$$\begin{aligned} Y(k) &= [C(k) + I(k) + G(k - 1)] \\ I(k) &= (\alpha + \Delta\alpha)[Y(k - 1) - Y(k - 2)] \\ C(k) &= (\beta + \Delta\beta)Y^v(k - 1) \end{aligned} \tag{13}$$

where Y is the deviation of the national income from the desired national income, I is the deviation of the induced private investment from the desired induced private investment, C is the deviation of the consumption expenditure from the desired consumption expenditure, G is the deviation of the government expenditure from the desired government expenditure decided at the end of period $(k - 1)$ for period k , α is the accelerator coefficient, β is the marginal propensity to consume parameter and v is the consume parameter ($v \geq 1$). $\Delta\alpha$ and $\Delta\beta$ are the uncertain accelerator coefficient and marginal propensity to consume parameter, respectively. We assume that $|\Delta\alpha| \leq 0.1\alpha$ and $|\Delta\beta| \leq 0.1\beta$.

Eliminating $C(k)$ and $I(k)$ in the above equations, we have

$$Y(k) = (\beta + \Delta\beta)Y^v(k - 1) + (\alpha + \Delta\alpha)Y(k - 1) + G(k - 1) - (\alpha + \Delta\alpha)Y(k - 2). \tag{14}$$

By shifting one step forward and giving $x_1(k) = Y(k - 1)$, $x_2(k) = Y(k)$ and $u(k) = G(k)$, (14) becomes

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \end{bmatrix} = \begin{bmatrix} x_2(k) \\ \left(\begin{array}{c} -(\alpha + \Delta\alpha)x_1(k) \\ +(\alpha + \Delta\alpha)x_2(k) \\ +(\beta + \Delta\beta)x_2^v(k) \end{array} \right) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(k). \tag{15}$$

Converting (15) to continuous-time system model, we have

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} x_2(t) + x_1(t) \\ \left(\begin{array}{c} -(\alpha + \Delta\alpha)x_1(t) \\ +(\alpha + \Delta\alpha)x_2(t) \\ +(\beta + \Delta\beta)x_2^v(t) + x_2(t) \end{array} \right) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t). \tag{16}$$

Based on [37], the general economic situations could be aggregated into three modes as shown in Table I:

TABLE I
ECONOMIC TERMINOLOGY.

Mode z	Terminology	$\alpha(z) \pm \Delta\alpha(z)$	$\beta(z) \pm \Delta\beta(z)$
1	Normal	$2.5 \pm 10\%$	$0.3 \pm 10\%$
2	Boom	$43.7 \pm 10\%$	$-0.7 \pm 10\%$
3	Slump	$-5.3 \pm 10\%$	$0.9 \pm 10\%$

The transition probability matrix that relates the three operation modes is given as follows:

$$P_{zk} = \begin{bmatrix} 0.67 & 0.17 & 0.16 \\ 0.30 & 0.47 & 0.23 \\ 0.26 & 0.10 & 0.64 \end{bmatrix}.$$

Assuming $v = 2$, (16) can be re-expressed as

$$\begin{aligned} \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} &= \begin{bmatrix} 1 & 1 \\ -\alpha(z) & \left[\begin{array}{c} \alpha(z) + 1 \\ +\beta(z)x_2(t) \end{array} \right] \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \\ &+ \begin{bmatrix} 0 & 0 \\ 0.1 & 0 \end{bmatrix} w(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t) \\ &+ \begin{bmatrix} 0 & 0 \\ -\Delta\alpha(z) & \left[\begin{array}{c} \Delta\alpha(z) \\ +\Delta\beta(z)x_2(t) \end{array} \right] \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \\ z(t) &= \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \\ y(t) &= Jx(t) + [0 \ 0.1]w(t) \end{aligned} \tag{17}$$

where $x_1(t)$ and $x_2(t)$ are the state vectors, $u(t)$ is the controlled input which represents the deviation of the government expenditure from the desired government expenditure, $w(t)$ is the disturbance input which represents the unexpected behavior of the economy, $z(t)$ is the controlled output, $y(t)$ is the measured output and J is the sensor matrix.

The control objective is to control the state variable $x_2(t)$ for the range $x_2(t) \in [N_1 \ N_2]$. For the sake of simplicity, we will use as few rules as possible. Note that Figure 1 shows the plot of the membership functions represented by

$$M_1(x_2(t)) = \frac{-x_2(t) + N_2}{N_2 - N_1} \text{ and } M_2(x_2(t)) = \frac{x_2(t) - N_1}{N_2 - N_1}.$$

Knowing that $x_2(t) \in [N_1 \ N_2]$, the nonlinear system (17) can be approximated by the following TS fuzzy model:

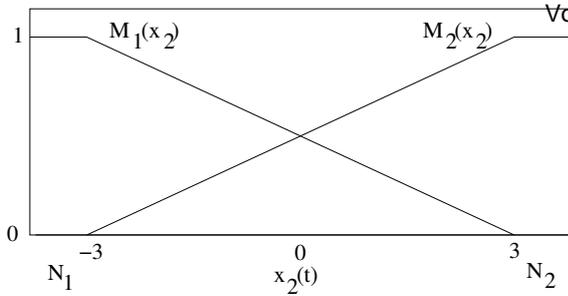


Fig. 1. Membership functions for the two fuzzy set.

Plant Rule 1: IF $x_2(t)$ is $M_1(x_2(t))$ THEN

$$\begin{aligned}\dot{x}(t) &= [A_1(\iota) + \Delta A_1(\iota)]x(t) \\ &\quad + B_{11}(\iota)w(t) + B_{21}(\iota)u(t), \quad x(0) = 0, \\ z(t) &= C_{11}(\iota)x(t), \\ y(t) &= C_{21}(\iota)x(t) + D_{211}(\iota)w(t).\end{aligned}$$

Plant Rule 2: IF $x_2(t)$ is $M_2(x_2(t))$ THEN

$$\begin{aligned}\dot{x}(t) &= [A_2(\iota) + \Delta A_2(\iota)]x(t) \\ &\quad + B_{12}(\iota)w(t) + B_{22}(\iota)u(t), \quad x(0) = 0, \\ z(t) &= C_{12}(\iota)x(t), \\ y(t) &= C_{22}(\iota)x(t) + D_{212}(\iota)w(t)\end{aligned}$$

where $x(t) = [x_1^T(t) \ x_2^T(t)]^T$,

$$A_1(1) = \begin{bmatrix} 1 & 1 \\ -2.5 & 3.5 + 0.7N_1 \end{bmatrix},$$

$$A_2(1) = \begin{bmatrix} 1 & 1 \\ -2.5 & 3.5 + 0.7N_2 \end{bmatrix},$$

$$A_1(2) = \begin{bmatrix} 1 & 1 \\ -43.7 & 44.5 + 1.7N_1 \end{bmatrix},$$

$$A_2(2) = \begin{bmatrix} 1 & 1 \\ -43.7 & 44.5 + 1.7N_2 \end{bmatrix},$$

$$A_1(3) = \begin{bmatrix} 1 & 1 \\ 5.3 & -4.3 + 0.1N_1 \end{bmatrix},$$

$$A_2(3) = \begin{bmatrix} 1 & 1 \\ 5.3 & -4.3 + 0.1N_2 \end{bmatrix},$$

$$B_{11}(\iota) = B_{12}(\iota) = \begin{bmatrix} 0 & 0 \\ 0.1 & 0 \end{bmatrix},$$

$$B_{21}(\iota) = B_{22}(\iota) = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

$$C_{11}(\iota) = C_{12}(\iota) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad C_{21}(\iota) = C_{22}(\iota) = J,$$

$$D_{211}(\iota) = D_{212}(\iota) = \begin{bmatrix} 0 & 0.1 \end{bmatrix},$$

$$\Delta A_1(\iota) = F(x(t), \iota, t)H_{11}(\iota)$$

$$\text{and } \Delta A_2(\iota) = F(x(t), \iota, t)H_{12}(\iota).$$

Now, by assuming that in (17), $\|F(x(t), \iota, t)\| \leq \rho(\iota) = 1$, we have

$$H_{11}(\iota) = \begin{bmatrix} 0 & 0 \\ -0.1\alpha(\iota) & 0.1\alpha(\iota) + 0.1\beta(\iota)N_1 \end{bmatrix}$$

$$\text{and } H_{12}(\iota) = \begin{bmatrix} 0 & 0 \\ -0.1\alpha(\iota) & 0.1\alpha(\iota) + 0.1\beta(\iota)N_2 \end{bmatrix}.$$

In this simulation, we select $N_1 = -3$ and $N_2 = 3$. Using the LMI optimization algorithm and Theorem 1 with $\gamma = 1$, we obtain

$$K_1(1) = \begin{bmatrix} -20.7511 & -8.7443 \end{bmatrix},$$

$$K_2(1) = \begin{bmatrix} -20.7510 & -12.9443 \end{bmatrix},$$

$$K_1(2) = \begin{bmatrix} 27.3538 & -45.1409 \end{bmatrix},$$

$$K_2(2) = \begin{bmatrix} 11.6005 & -60.1228 \end{bmatrix},$$

$$K_1(3) = \begin{bmatrix} -25.8817 & -2.1590 \end{bmatrix},$$

$$K_2(3) = \begin{bmatrix} -25.8817 & -2.7590 \end{bmatrix}.$$

The resulting fuzzy controller is

$$u(t) = \sum_{j=1}^2 \mu_j K_j(\iota) x(t)$$

where

$$\mu_1 = M_1(x_2(t)) \quad \text{and} \quad \mu_2 = M_2(x_2(t)).$$

Remark 1: The robust fuzzy state-feedback controller guarantees that the \mathcal{L}_2 -gain, γ , is less than the prescribed value. Figure 2 shows the changing between modes during the simulation with the initial mode 1. The disturbance input signal, $w(t)$, which was used during simulation is the rectangular signal (magnitude 0.1 and frequency 10 Hz). The ratios of the regulated output energy to the disturbance input noise energy for both cases are depicted in Figure 3. After time = 3, the ratio of the regulated output energy to the disturbance input noise energy tends to a constant value which is about 0.18. Thus, $\gamma = \sqrt{0.18} = 0.424$, which is less than the prescribed value 1. \square

V. CONCLUSION

This paper has proposed a technique for designing an \mathcal{H}_∞ state-feedback controller for a class of fuzzy Markovian jump dynamic systems that guarantees the \mathcal{L}_2 -gain from an exogenous input to a regulated output is less or equal to a prescribed value. Based on an LMI approach, LMI-based sufficient conditions for the uncertain Markovian jump Takagi-Sugeno fuzzy model to have an \mathcal{H}_∞ performance are established. The effectiveness of the proposed design methodology is demonstrated through a numerical simulation system.

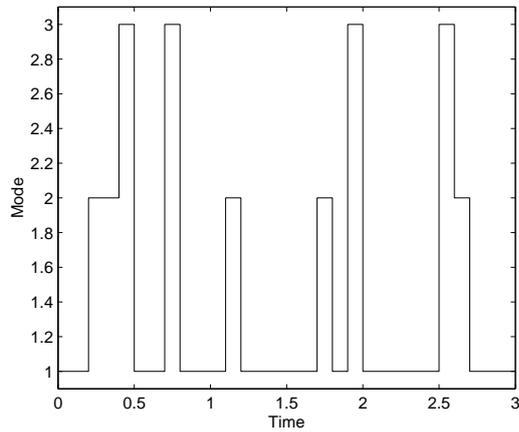


Fig. 2. The result of the changing between modes during the simulation with the initial mode 1.

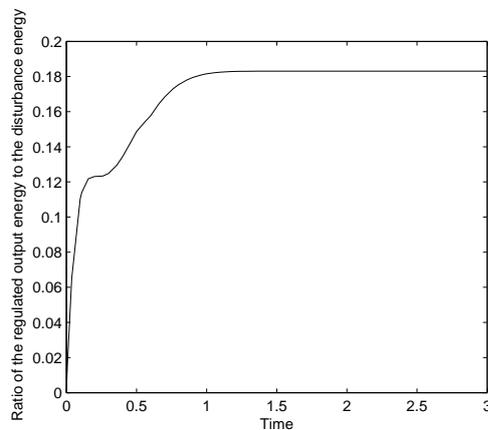


Fig. 3. The ratio of the regulated output energy to the disturbance noise energy, $\left(\frac{\int_0^{T_f} z^T(t)z(t)dt}{\int_0^{T_f} w^T(t)w(t)dt} \right)$.

REFERENCES

- [1] S.P. Sethi and Q. Zhang, *Hierarchical Decision Making in Stochastic Manufacturing Systems*, Birkhauser, Boston, 1994.
- [2] M. Mariton, *Jump Linear Systems in Automatic Control*, Dekker, New York, 1990.
- [3] E.K. Boukas and A. Haurie, "Manufacturing flow control and preventive maintenance: A stochastic control approach", *IEEE Trans. Automat. Contr.*, vol. 35, pp. 1024–1031, 1990.
- [4] E.K. Boukas, Q. Zhang, and G. Yin, "Robust production and maintenance planning in stochastic manufacturing systems", *IEEE Trans. Automat. Contr.*, vol. 40, pp. 1098–1102, 1995.
- [5] E.K. Boukas and P. Shi, "Stochastic stability and guaranteed cost control of discrete-time uncertain systems with Markovian jumping parameters", *Internat. J. Robust Nonlinear Contr.*, vol. 8, pp. 1155–1167, 1998.
- [6] O.L.V. Costa and M.D. Fragoso, "Stability results for discrete-time linear systems with Markovian jumping parameters", *J. Math. Anal. Appl.*, vol. 179, pp. 154–178, 1993.
- [7] V. Dragan, P. Shi, and E.K. Boukas, "Control of singularly perturbed systems with Markovian jump parameters: an \mathcal{H}_∞ approach", *Automatica*, vol. 35, pp. 1369–1378, 1999.
- [8] K. Ito and H.P. McKean, *Diffusion Processes and Their Sample Paths*, Springer-Verlag, Berlin, 1965.
- [9] Y. Ji and H.J. Chizeck, "Controllability, stabilizability, and continuous-time Markovian jump linear quadratic control", *IEEE Trans. Automat. Contr.*, vol. 35, pp. 777–788, 1990.

- [10] N.N. Krasovskii and E.A. Lidskii, "Analysis design of controller in systems with random attributes-Part 1", *Automat. Remote Contr.*, vol. 22, pp. 1021–1025, 1961.
- [11] P. Shi and E.K. Boukas, " \mathcal{H}_∞ control for Markovian jumping linear systems with parametric uncertainty", *J. Optim. Theory Appl.* vol. 95, pp. 75–99, 1997.
- [12] E. K. Boukas, Peng Shi, S.K. Nguang, and R.K. Agarwal, "Robust \mathcal{H}_∞ control of a class of nonlinear systems with markovian jumping parameters", *IEEE American Contr. Conf.*, pp. 970–976, 1999.
- [13] C.E. de Souza and M.D. Fragoso, " \mathcal{H}_∞ control for linear systems with Markovian jumping parameters", *Control Theory Adv. Technol.* vol. 9, pp. 457–466, 1993.
- [14] M.D.S. Aliyu and E.K. Boukas, " \mathcal{H}_∞ control for markovian jump nonlinear systems", *37th IEEE Conf. on Decision and Contr.*, pp. 766–771, 1998.
- [15] K. Tanaka and M. Sugeno, "Stability analysis and design of fuzzy control systems", *Fuzzy Sets Syst.*, vol. 45, pp. 135–156, 1992.
- [16] K. Tanaka, "Stability and stabilizability of fuzzy neural linear control systems", *IEEE Trans. Fuzzy Syst.*, vol. 3, pp. 438–447, 1995.
- [17] K. Tanaka, T. Ikeda, and H. O. Wang, "Robust stabilization of a class of uncertain nonlinear systems via fuzzy control: Quadratic stabilizability, \mathcal{H}_∞ control theory, and linear matrix inequality", *IEEE Trans. Fuzzy Syst.*, vol. 4, pp. 1–13, 1996.
- [18] H. O. Wang, K. Tanaka, and M. F. Griffin, "An approach to fuzzy control of nonlinear systems: Stability and design issues", *IEEE Trans. Fuzzy Syst.*, vol. 4, pp. 14–23, 1996.
- [19] S. G. Cao, N. W. Ree, and G. Feng, "Quadratic stability analysis and design of continuous-time fuzzy control systems", *Int. J. Syst. Sci.*, vol. 27, pp. 193–203, 1996.
- [20] W. Assawinchaichote and S.K. Nguang, "Fuzzy observer-based controller design for singularly perturbed nonlinear systems: An LMI approach", *IEEE Conf. on Decision and Contr.*, pp. 2165–2170, 2002.
- [21] T. Takagi and M. Sugeno, "Fuzzy identification of systems and its applications to modelling and control", *IEEE Trans. Syst. Man. Cybern.*, vol. 15, pp. 116–132, 1985.
- [22] C. L. Chen, P. C. Chen, and C. K. Chen, "Analysis and design of fuzzy control system", *Fuzzy Sets Syst.*, vol. 57, pp. 125–140, 1995.
- [23] X. J. Ma, Z. Q. Sun, and Y. Y. He, "Analysis and design of fuzzy controller and fuzzy observer", *IEEE Trans. Fuzzy Syst.*, vol. 6, pp. 41–51, 1998.
- [24] B. S. Chen, C. S. Tseng, and H. J. Uang, "Mixed $\mathcal{H}_2/\mathcal{H}_\infty$ fuzzy output feedback control design for nonlinear dynamic systems: An LMI approach", *IEEE Trans. Fuzzy Syst.*, vol. 8, pp. 249–265, 2000.
- [25] S.K. Nguang and P. Shi, "Stabilisation of a class of nonlinear time-delay systems using fuzzy models", *Proc. 39th IEEE Conf. on Decision and Contr.*, pp. 4415–4419, 2000.
- [26] S. K. Nguang and P. Shi, " \mathcal{H}_∞ fuzzy output feedback control design for nonlinear systems: An LMI approach", *40th IEEE Conf. on Decision and Contr.*, pp. 2501–2506, 2001.
- [27] S. K. Nguang and P. Shi, "Fuzzy \mathcal{H}_∞ output feedback control of nonlinear systems under sampled measurements", *40th IEEE Conf. on Decision and Contr.*, pp. 120–126, 2001.
- [28] M. Teixeira and S. H. Zak, "Stabilizing controller design for uncertain nonlinear systems using fuzzy models", *IEEE Trans. Fuzzy Syst.*, vol. 7, pp. 133–142, 1999.
- [29] S. H. Zak, "Stabilizing fuzzy system models using linear controllers", *IEEE Trans. Fuzzy Syst.*, vol. 7, pp. 236–240, 1999.
- [30] L. X. Wang, *A course in fuzzy systems and control*. Englewood Cliffs, NJ: Prentice-Hall, 1997.
- [31] S. K. Nguang and P. Shi, " \mathcal{H}_∞ fuzzy output feedback control design for nonlinear systems: An LMI approach", *IEEE Trans. Fuzzy Syst.*, vol. 11, pp. 331–340, 2003.
- [32] S. K. Nguang and W. Assawinchaichote, " \mathcal{H}_∞ filtering for fuzzy dynamic systems with pole placement", *IEEE Trans. Circuits Syst. I*, vol. 50, pp. 1503–1508, 2003.
- [33] W. Assawinchaichote and S. K. Nguang, " \mathcal{H}_∞ filtering for nonlinear singularly perturbed systems with pole placement constraints: An LMI approach", *IEEE Trans. Signal Processing*, vol. 52, pp. 579–588, 2004.
- [34] W. M. Wonham, "Random differential equations in control theory," *Probabilistic Methods in App. Math.*, vol. 2, pp. 131–212, 1970.
- [35] E. B. Dynkin, *Markov Process*, Berlin: Springer-Verlag, 1965.
- [36] H. E. Nusse and C. H. Hommes, "Resolution of chaos with application to a modified Samuelson model," *J. of Economic Dyn. Contr.*, vol. 14, pp. 1–19, 1990.
- [37] W. P. Blair, Jr. and D. D. Sworder, "Continuous-time regulation of a class of econometric models," *IEEE Trans. Sys. Man and Cybern.*, vol. 5, pp. 341–346, 1975.