Research Article

H_∞ Robust Tracking Control of Stochastic T-S Fuzzy Systems with Poisson Jumps

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A robust adaptive H_∞ tracking control design for nonlinear stochastic systems with both Brownian motion and Poisson jumps is proposed, which is based on Takagi–Sugeno (T-S) type fuzzy techniques. Because the state of to-be-controlled systems cannot be known exactly, to overcome this difficulty, the state estimation systems and error estimation systems are introduced to obtain an augmented system. By using the fuzzy systems to approximate the nonlinear systems, an adaptive fuzzy control is employed to achieve the desired H_∞ tracking performance for stochastic systems with exogenous disturbance. A simulation example is presented to illustrate the tracking performance of the proposed design method.

1. Introduction

Adaptive control theory is a powerful methodology which has been widely applied to design feedback control for systems with parametric uncertainties or for plants with unknown structure or changing operating conditions [1, 2]. Because there are uncertainties in the systems, the laws of adaptive control design schemes no more depend on the fixed description of input-output relationships but are related to the estimation of the system's state or output and those estimating errors [3–6].

The robust H_∞ tracking control theory is a powerful methodology to design feedback controllers where the system parametric uncertainties are seen as the exogenous disturbance [7–9]. This methodology is widely applied in networked control systems [10], mobile robots [11], etc. The objective of the robust H_∞ tracking control design is to construct an adaptive controller which guarantees the H_∞ tracking control performance. Based on the system's structure, the robust H_∞ tracking control designing methods include linear H_∞ control and nonlinear H_∞ control. Linear H_∞ control design problems are based on solving a kind of algebra Riccati inequalities which can be solved by the

LMI's method. And the nonlinear H_∞ control design involves solving a nonlinear Hamilton–Jacobi inequality (HJI) [12]. However, it is very difficult to solve the Hamilton–Jacobi equalities or inequalities [13, 14]. In practice, to overcome this difficulty, the fuzzy methods have been applied to the H_∞ robust control design of nonlinear systems where the Takagi–Sugeno (T-S) type fuzzy is widely used [15–17].

Stochastic systems are applied in economics [18], biology [19], and natural science to describe the randomness in models [20–23]. Based on the distribution properties of the inserted random variables, stochastic systems include Itô-type systems driven by Brownian motion [24, 25], systems driven by Markovian jumps [26], systems driven by Poisson jumps or Lévy process [27], and their compound forms [28–30]. The linear stochastic H_∞ theory has been developed since 1990s via the linear matrix inequalities (LMI) approach [31]. The nonlinear stochastic H_∞ problems are solved by means of Hamilton–Jacobi equations [25]. In practice, there exist sudden shifts in the systems. In order to describe such phenomenon, Poisson jumps are inserted in the model, so the stochastic systems are driven not only by Brownian motion but also by Poisson jumps or Lévy process [27, 28]. The main complication in the H_∞ tracking control design problem

studied here is due to the presence of both deterministic, stochastic perturbations and Poisson jumps terms in the system. Nonlinear H_∞ tracking theory and fuzzy control design are combined together to construct the adaptive fuzzy-based controller which guarantees the H_∞ tracking control performance.

This paper is organized as follows: In Section 2, some lemmas about stochastic differential equations with Poisson jumps are reviewed, which will be used in the latter theoretical analysis and deductions. In Section 3, the theories of H_∞ tracking control are extended to the case of linear stochastic systems with Poisson jumps. In Section 4, the H_∞ tracking control design methods based on the Takagi–Sugeno type fuzzy techniques are applied to the nonlinear stochastic systems with Poisson jumps, and the H_∞ tracking controller is obtained. In Section 5, the air-to-air missile pursuit systems are presented to show the effectiveness of the proposed method.

Notation. For convenience, we adopt the following notations: $\mathbb{R}^{m \times n}$: the set of all real $m \times n$ matrices. $\mathbb{R}^n$: the set of all n -dimensional real vectors. $A > 0$ ($A \geq 0$): the positive definite (semidefinite) matrix A . A^T : the transpose of matrix A . I : the identity matrix with proper order. $\mathbb{E}[\xi]$: the expectation of random variable ξ . $|x|$: the Euclidean norm of vector $x \in \mathbb{R}^n$.

2. Preliminaries

Let $(\Omega, \mathcal{F}, \mathbb{F}, \text{Pr})$ be a complete probability space where $\mathbb{F} = \{\mathcal{F}_t : t \geq 0\}$ is a filtration generated by Brownian motion (Wiener process) $\{W(t), t \geq 0\}$ and Poisson process $\{N(t), t \geq 0\}$ which are two mutually independent stochastic processes:

- (i) $W(t)$ is a d -dimensional standard Brownian motion with $E[W(t)] = 0$ and $E[W(t)W(t)^T] = I_d$;
- (ii) $N(t)$ is a Poisson jump process with rate $\lambda > 0$ and $\mathbb{E}[N(t)] = \lambda t$.

Let

$$\mathcal{F}_t = \sigma(N(s) : s \leq t) \vee \sigma(W(s) : s \leq t) \vee \mathcal{N}, \quad (1)$$

where $\mathcal{N}$ denotes the totality of P -null sets. Then the filtration $\mathbb{F} = \{\mathcal{F}_t\}_{t \geq 0}$. We firstly review some basic theories of stochastic differential equations driven by both Brownian motion and Poisson jumps:

$$\begin{aligned} dx(t) &= f(t, x(t)) dt + \sigma(t, x(t)) dW(t) \\ &\quad + \gamma(t, x(t)) dN(t), \\ x(0) &= x_0 \in \mathbb{R}^n. \end{aligned} \quad (2)$$

Lemma 1. Let $f(t, x), \sigma(t, x), \gamma(t, x)$ be $\mathbb{R}^n$ -valued functions on $[0, T] \times \mathbb{R}^n$ and, for some positive constant K , satisfy the Lipschitz condition

$$\begin{aligned} |f(t, x) - f(t, y)| + |\sigma(t, x) - \sigma(t, y)| \\ + |\gamma(t, x) - \gamma(t, y)| \leq K|x - y|, \end{aligned} \quad (3)$$

and linear growth condition

$$|f(t, x)| + |\sigma(t, x)| + |\gamma(t, x)| \leq K|x| \quad (4)$$

for all $x, y \in \mathbb{R}^n, t \in [0, T]$. Then the stochastic differential equation (2) has a unique adapted solution with right continuation and left limitation.

Under the conditions of Lemma 1, we then review the Itô's formula of (2) (see [32], Chapter 4, Rule 4.24).

Lemma 2. Let $V(t, x)$ be twice continuously differentiable in x and once in t ; $x(t)$ is the solution of stochastic differential equation (2). Then

$$\begin{aligned} dV(t, x(t)) &= \left[V_t(t, x(t)) + V_x^T(t, x(t)) f(t, x(t)) \right. \\ &\quad \left. + \frac{1}{2} \sigma^T(t, x(t)) V_{xx}(t, x(t)) \sigma(t, x(t)) \right] dt \\ &\quad + V_x(t, x(t)) \sigma(t, x(t)) dW(t) \\ &\quad + [V(t, x(t) + \gamma(t, x(t))) - V(t, x(t))] dN(t). \end{aligned} \quad (5)$$

The following lemma is a kind of martingale inequality; see Proposition 7.15 in [33].

Lemma 3. For a finite $T_f > 0$, let $\{X_t\}_{0 \leq t \leq T_f}$ be a submartingale (or martingale, or supermartingale) with respect to filtrations $\mathbb{F} = \{\mathcal{F}_t\}_{0 \leq t \leq T_f}$. Then for any $r > 0$, there exists

$$\text{Pr} \left\{ \sup_{0 \leq t \leq T_f} |X_t| \geq r \right\} \leq \frac{3}{r} \sup_{0 \leq t \leq T_f} \mathbb{E}|X_t|. \quad (6)$$

Remark 4. Because Brownian motion $W(t)$ is a martingale with respect to filtration $\mathbb{F}$, and Poisson process $N(t)$ is a submartingale, by Lemma 3, for every finite $T_f > 0$, there exist

$$\begin{aligned} \text{Pr} \left\{ \sup_{0 \leq t \leq T_f} |W(t)| \geq r \right\} &\leq \frac{3}{r} \sup_{0 \leq t \leq T_f} \mathbb{E}|W(t)| \\ &= \frac{3}{r} \sup_{0 \leq t \leq T_f} \sqrt{\frac{2t}{\pi}} = \frac{3}{r} \sqrt{\frac{2T_f}{\pi}}, \end{aligned} \quad (7)$$

and

$$\begin{aligned} \text{Pr} \left\{ \sup_{0 \leq t \leq T_f} |N(t)| \geq r \right\} &\leq \frac{3}{r} \sup_{0 \leq t \leq T_f} \mathbb{E}|N(t)| = \frac{3}{r} \sup_{0 \leq t \leq T_f} \lambda t \\ &= \frac{3\lambda T_f}{r}, \end{aligned} \quad (8)$$

or equivalently,

$$\text{Pr} \left\{ \sup_{0 \leq t \leq T_f} |W(t)| < r \right\} \geq 1 - \frac{3}{r} \sqrt{\frac{2T_f}{\pi}}, \quad (9)$$

and

$$\Pr \left\{ \sup_{0 \leq t \leq T_f} |N(t)| < r \right\} \geq 1 - \frac{3\lambda T_f}{r}. \quad (10)$$

Therefore, when r is large enough, $|W(t)|$ and $N(t)$ have upper bound with probability $p_1(r) = 1 - (3/r)\sqrt{2T_f/\pi}$ and $p_2(r) = 1 - 3\lambda T_f/r$, respectively. Furthermore, $p_1(r) \rightarrow 1$ and $p_2(r) \rightarrow 1$ when $r \rightarrow +\infty$.

3. H_∞ Robust Tracking Control of Linear Systems

Consider the linear control system with the following forms:

$$\begin{aligned} dx(t) &= [Ax(t) + Bu(t) + Ew(t)] dt \\ &\quad + [A_1x(t) + E_1w(t)] dW_1(t) \\ &\quad + [A_2x(t) + E_2w(t)] dN_1(t), \\ y(t) &= Cx(t) + v, \end{aligned} \quad (11)$$

where $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times n_u}$, $E, E_1, E_2 \in \mathbb{R}^{n \times n_w}$, $C \in \mathbb{R}^{n_y \times n}$, and $D \in \mathbb{R}^{n_y \times n_v}$ are the system's coefficient matrices; $x(t) \in \mathbb{R}^n$ is the state, $y(t) \in \mathbb{R}^{n_y}$ is the measurement, $w(t) \in \mathbb{R}^{n_w}$ and $v(t) \in \mathbb{R}^{n_v}$ are the exogenous disturbances; and $W_1(t)$ is the standard 1-dimensional Wiener process and $N_1(t)$ is the Poisson process with Poisson intensity $\lambda > 0$.

Now, we review the basic theory of stochastic differential equations driven by both martingale and Poisson jumps. In order to design the tracking control of system (11), a reference model is suggested as follows:

$$dx_r(t) = [A_r x_r(t) + r(t)] dt, \quad (12)$$

where $x_r(t) \in \mathbb{R}^n$ is the desired reference state to be tracked by $x(t)$, $A_r \in \mathbb{R}^{n \times n}$ is a specified asymptotically stable matrix, and $r(t)$ is a bounded reference input at the steady state, $x_r(t) = -A_r^{-1}r(t)$. In practice, $r(t)$ and A_r are given by user or designer to specify the transient and the steady state of reference signal $x_r(t)$ to be tracked.

Denote the tracking errors as

$$e_r(t) = x(t) - x_r(t). \quad (13)$$

For the tracking error $e_r(t)$, we consider the H_∞ robust tracking performance as follows:

$$\frac{\int_0^{t_f} \mathbb{E} \{e_r^T(t) Q e_r(t)\} dt}{\int_0^{t_f} \mathbb{E} [\bar{w}^T(t) \bar{w}(t)] dt} \leq \rho^2. \quad (14)$$

Here Q is a positive definite matrix, $t_f > 0$ is the terminal time of control, and $\bar{w}(t) = [v(t)^T w(t)^T r(t)^T]^T$. The physical meaning of (14) is that the effect of any $\bar{w}$ on tracking error $e_r(t)$ must be attenuated below a desired level $\rho > 0$ from the viewpoint of energy. The following observer is proposed to deal with the state estimation of linear system (11):

$$\begin{aligned} d\hat{x}(t) &= [A\hat{x}(t) + Bu(t) + L(y(t) - \hat{y}(t))] dt, \\ \hat{y}(t) &= C\hat{x}(t). \end{aligned} \quad (15)$$

Denote the estimation errors as

$$e(t) = x(t) - \hat{x}(t). \quad (16)$$

Combining (11) and (15), we get

$$\begin{aligned} de(t) &= [(A - LC)e(t) - Lv(t)] dt \\ &\quad + [A_1x(t) + w(t)] dW_1(t) \\ &\quad + [A_2x(t) + w(t)] dN_1(t). \end{aligned} \quad (17)$$

Suppose the controller $u(t)$ has the form as

$$u(t) = K[\hat{x}(t) - x_r(t)]. \quad (18)$$

The performance (14) considering control effort is revised as

$$\frac{\int_0^{t_f} \mathbb{E} \{e_r^T(t) Q e_r(t) + u^T(t) R u(t)\} dt}{\int_0^{t_f} \mathbb{E} [\bar{w}^T(t) \bar{w}(t)] dt} \leq \rho^2, \quad (19)$$

where R is a positive definite matrix. Let $\tilde{x} = [e^T, x^T, x_r^T]^T$ and substitute (18) into (11); then system (11) and (17) can be augmented as the following form

$$\begin{aligned} d\tilde{x}(t) &= [\tilde{A}\tilde{x}(t) + \tilde{E}\tilde{w}(t)] dt \\ &\quad + [\tilde{A}_1\tilde{x}(t) + \tilde{E}_1\tilde{w}(t)] dW_1(t) \\ &\quad + [\tilde{A}_2\tilde{x}(t) + \tilde{E}_2\tilde{w}(t)] dN_1(t), \end{aligned} \quad (20)$$

and the H_∞ performance of (19) equals

$$\int_0^{t_f} \tilde{x}^T(t) \bar{Q} \tilde{x}(t) dt \leq \rho^2 \int_0^{t_f} \bar{w}^T(t) \bar{w}(t) dt \quad (21)$$

where

$$\begin{aligned} \tilde{A} &= \begin{bmatrix} A - LC & 0 & 0 \\ -BK & A + BK & -BK \\ 0 & 0 & A_r \end{bmatrix}, \\ \tilde{A}_1 &= \begin{bmatrix} 0 & A_1 & 0 \\ 0 & A_1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \\ \tilde{A}_2 &= \begin{bmatrix} 0 & A_2 & 0 \\ 0 & A_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \end{aligned}$$

$$\begin{aligned}
\tilde{E} &= \begin{bmatrix} -L & E & 0 \\ 0 & E & 0 \\ 0 & 0 & I \end{bmatrix}, \\
\tilde{E}_1 &= \begin{bmatrix} 0 & E_1 & 0 \\ 0 & E_1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \\
\tilde{E}_2 &= \begin{bmatrix} 0 & E_2 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \\
\tilde{Q} &= \begin{bmatrix} K^T R K & -K^T R K & K^T R K \\ -K^T R K & K^T R K + Q & -K^T R K - Q \\ K^T R K & -K^T R K - Q & K^T R K + Q \end{bmatrix}.
\end{aligned} \tag{22}$$

In order to achieve the H_∞ tracking performance (19) with a prescribed attenuation level ρ , an auxiliary symmetric positive definite matrix $\tilde{P}$ is suggested. The matrices of $\tilde{A}$ and $\tilde{E}$ include the to-be-designed matrices K and L . If the initial state $x(0)$, $x_r(0)$ and the estimation error $e(0)$ are also considered, the performance of (19) can be described as follows.

$$\begin{aligned}
&\int_0^{t_f} \mathbb{E} \{e_r^T(t) Q e_r(t) + u^T(t) R u(t)\} dt \\
&\leq \tilde{x}(0)^T \tilde{P} \tilde{x}(0) + \rho^2 \int_0^{t_f} \mathbb{E} [\tilde{w}^T(t) \tilde{w}(t)] dt
\end{aligned} \tag{23}$$

Theorem 5. Suppose $\tilde{P} \in \mathcal{S}_+^{3n}(\mathbb{R})$, $K \in \mathbb{R}^{n_u \times n}$, $L \in \mathbb{R}^{n \times n_y}$ constitute the solution of the following Riccati matrix inequality:

$$\mathcal{H}(\tilde{P}) \leq 0, \tag{24}$$

$$\rho^2 I - \tilde{E}_1^T \tilde{P} \tilde{E}_1 - \lambda \tilde{E}_2^T \tilde{P} \tilde{E}_2 > 0 \tag{25}$$

where

$$\begin{aligned}
\mathcal{H}(\tilde{P}) &= \tilde{A}^T \tilde{P} + \tilde{P} \tilde{A} + \tilde{A}_1^T \tilde{P} \tilde{A}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{A}_2 + \tilde{Q} \\
&+ (\tilde{P} \tilde{E} + \tilde{A}_1^T \tilde{P} \tilde{E}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{E}_2) \\
&\times (\rho^2 I - \tilde{E}_1^T \tilde{P} \tilde{E}_1 - \lambda \tilde{E}_2^T \tilde{P} \tilde{E}_2)^{-1} \\
&\cdot (\tilde{P} \tilde{E} + \tilde{A}_1^T \tilde{P} \tilde{E}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{E}_2)^T.
\end{aligned} \tag{26}$$

Then the H_∞ tracking control performance in (24) is guaranteed for a prescribed ρ^2 .

Proof. Let $\tilde{V}(\tilde{x}) = \tilde{x}^T \tilde{P} \tilde{x}$, $\tilde{x} \in \mathbb{R}^{3n}$. By Itô formula, we get

$$\begin{aligned}
\tilde{V}(\tilde{x}(t_f)) - \tilde{V}(\tilde{x}(0)) &= \int_0^{t_f} \{ \tilde{x}^T(t) \\
&\cdot [\tilde{A}^T \tilde{P} + \tilde{P} \tilde{A} + \tilde{A}_1^T \tilde{P} \tilde{A}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{A}_2] \tilde{x}(t) + 2 \tilde{x}^T(t) \\
&\cdot [\tilde{P} \tilde{E} + \tilde{A}_1^T \tilde{P} \tilde{E}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{E}_2] \tilde{w}(t) \\
&+ \tilde{w}^T [\tilde{E}_1^T \tilde{P} \tilde{E}_1 + \lambda \tilde{E}_2^T \tilde{P} \tilde{E}_2] \tilde{w} \} dt + 2 \int_0^{t_f} \tilde{x}^T(t) \\
&\cdot \tilde{P} [\tilde{A}_1 \tilde{x}(t) + \tilde{E}_1 \tilde{w}(t)] dW_1(t) \\
&+ 2 \int_0^{t_f} \tilde{x}^T(t) \tilde{P} [\tilde{A}_2 \tilde{x}(t) + \tilde{E}_2 \tilde{w}(t)] d\tilde{N}_1(t).
\end{aligned} \tag{27}$$

Taking expectation on the both sides, we obtain

$$\begin{aligned}
\mathbb{E} [\tilde{V}(\tilde{x}(t_f))] &= \tilde{V}(\tilde{x}(0)) + \int_0^{t_f} \mathbb{E} \{ \tilde{x}^T(t) \\
&\cdot [\tilde{A}^T \tilde{P} + \tilde{P} \tilde{A} + \tilde{A}_1^T \tilde{P} \tilde{A}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{A}_2] \tilde{x}(t) + 2 \tilde{x}^T(t) \\
&\cdot [\tilde{P} \tilde{E} + \tilde{A}_1^T \tilde{P} \tilde{E}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{E}_2] \tilde{w}(t) \\
&+ \tilde{w}^T [\tilde{E}_1^T \tilde{P} \tilde{E}_1 + \lambda \tilde{E}_2^T \tilde{P} \tilde{E}_2] \tilde{w} \} dt.
\end{aligned} \tag{28}$$

Thus, we have

$$\begin{aligned}
&\int_0^{t_f} \mathbb{E} [\tilde{x}^T(t) \tilde{Q} \tilde{x}(t)] dt = \tilde{V}(\tilde{x}(0)) - \mathbb{E} [\tilde{V}(\tilde{x}(t_f))] \\
&+ \int_0^{t_f} \mathbb{E} \{ \tilde{x}^T(t) \\
&\cdot [\tilde{A}^T \tilde{P} + \tilde{P} \tilde{A} + \tilde{A}_1^T \tilde{P} \tilde{A}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{A}_2 + \tilde{Q}] \tilde{x}(t) \\
&+ 2 \tilde{x}^T(t) [\tilde{P} \tilde{E} + \tilde{A}_1^T \tilde{P} \tilde{E}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{E}_2] \tilde{w}(t) \\
&- \tilde{w}^T [\rho^2 I - \tilde{E}_1^T \tilde{P} \tilde{E}_1 - \lambda \tilde{E}_2^T \tilde{P} \tilde{E}_2] \tilde{w} + \rho^2 \tilde{w}^T(t) \\
&\cdot \tilde{w}(t) \} dt.
\end{aligned} \tag{29}$$

Completing the square for $\tilde{w}$, we have

$$\begin{aligned}
&\int_0^{t_f} \mathbb{E} [\tilde{x}^T(t) \tilde{Q} \tilde{x}(t)] dt \\
&= \tilde{V}(\tilde{x}(0)) + \rho^2 \int_0^{t_f} \mathbb{E} [\tilde{w}^T(t) \tilde{w}(t)] dt \\
&+ \int_0^{t_f} \mathbb{E} \{ \tilde{x}^T(t) \tilde{\mathcal{H}}(\tilde{P}) \tilde{x}(t) \} dt \\
&- \mathbb{E} [\tilde{V}(\tilde{x}(t_f))] \\
&- \int_0^{t_f} \mathbb{E} [\| \tilde{w}(t) - \tilde{M}^{-1} \tilde{M}_1^T \tilde{x}(t) \|_{\tilde{R}}^2] dt
\end{aligned} \tag{30}$$

where $\tilde{M} = \rho^2 I - \tilde{E}_1^T \tilde{P} \tilde{E}_1 - \lambda \tilde{E}_2^T \tilde{P} \tilde{E}_2$ and $\tilde{M}_1 = \tilde{P} \tilde{E} + \tilde{A}_1^T \tilde{P} \tilde{E}_1 + \lambda \tilde{A}_2^T \tilde{P} \tilde{E}_2$. Together with (24), inequality (24) is proved. This ends the proof. $\square$

In order to find a solution for matrix inequality (24), suppose $\tilde{P}$ has the following block form

$$\tilde{P} = \begin{bmatrix} P_{11} & 0 & 0 \\ 0 & P_{22} & 0 \\ 0 & 0 & P_{33} \end{bmatrix}, \quad (31)$$

and then

$$\mathcal{H}(\tilde{P}) = \begin{bmatrix} \tilde{\mathcal{H}}_{11} & \tilde{\mathcal{H}}_{12} & \tilde{\mathcal{H}}_{13} \\ * & \tilde{\mathcal{H}}_{22} & \tilde{\mathcal{H}}_{23} \\ * & * & \tilde{\mathcal{H}}_{33} \end{bmatrix}, \quad (32)$$

where

$$\begin{aligned} \tilde{\mathcal{H}}_{11} &= A^T P_{11} + P_{11} A - C^T L^T P_{11} - P_{11} L C + K^T R K \\ &\quad + \frac{1}{\rho^2} P_{11} L L^T P_{11} + P_{11} E M^{-1} E^T P_{11}, \\ \tilde{\mathcal{H}}_{12} &= -K^T B^T P_{22} + P_{11} E M^{-1} [E^T P_{22} \\ &\quad + E_1^T (P_{11} + P_{22}) A_1 + \lambda E_2^T (P_{11} + P_{22}) A_2] \\ &\quad - K^T R K, \\ \tilde{\mathcal{H}}_{13} &= K^T R K, \\ \tilde{\mathcal{H}}_{22} &= (A^T + K^T B^T) P_{22} + P_{22} (A + B K) + Q \\ &\quad + K^T R K + A_1^T (P_{11} + P_{22}) A_1 + \lambda A_2^T (P_{11} + P_{22}) \\ &\quad \cdot A_2 + [P_{22} E + A_1^T (P_{11} + P_{22}) E_1 \\ &\quad + \lambda A_2^T (P_{11} + P_{22}) E_2] M^{-1} [E^T P_{22} \\ &\quad + E_1^T (P_{11} + P_{22}) A_1 + \lambda E_2^T (P_{11} + P_{22}) A_2], \\ \tilde{\mathcal{H}}_{23} &= -P_{22} B K - K^T R K - Q, \\ \tilde{\mathcal{H}}_{33} &= A_r^T P_{33} + P_{33} A_r + Q + K^T R K + \frac{1}{\rho^2} P_{33} P_{33}, \end{aligned} \quad (33)$$

and

$$M = \rho^2 I - E_1^T (P_{11} + P_{22}) E_1 - \lambda E_2^T (P_{11} + P_{22}) E_2. \quad (34)$$

Because

$$\begin{aligned} \tilde{\mathcal{H}}_{11} &= A^T P_{11} + P_{11} A + K^T R K + P_{11} E M^{-1} E^T P_{11} \\ &\quad - \rho^2 C^T C \\ &\quad + \frac{1}{\rho^2} (P_{11} L - \rho^2 C^T) (P_{11} L - \rho^2 C^T)^T, \end{aligned} \quad (35)$$

and

$$\begin{aligned} \tilde{\mathcal{H}}_{22} &= A^T P_{22} + P_{22} A - P_{22} B R^{-1} B^T P_{22} + Q + A_1^T (P_{11} \\ &\quad + P_{22}) A_1 + \lambda A_2^T (P_{11} + P_{22}) A_2 + [P_{22} E \\ &\quad + A_1^T (P_{11} + P_{22}) E_1 + \lambda A_2^T (P_{11} + P_{22}) E_2] \\ &\quad \cdot M^{-1} [E^T P_{22} + E_1^T (P_{11} + P_{22}) A_1 \\ &\quad + \lambda E_2^T (P_{11} + P_{22}) A_2] + (K + R^{-1} B^T P_{22})^T R (K \\ &\quad + R^{-1} B^T P_{22}), \end{aligned} \quad (36)$$

we take $L = \rho^2 P_{11}^{-1} C^T$ and $K = -R^{-1} B^T P_{22}$. Then

$$\begin{aligned} \tilde{\mathcal{H}}_{11} &= A^T P_{11} + P_{11} A + P_{22} B R^{-1} B^T P_{22} - \rho^2 C^T C \\ &\quad + P_{11} E M^{-1} E^T P_{11}, \\ \tilde{\mathcal{H}}_{12} &= P_{11} E M^{-1} [E^T P_{22} + E_1^T (P_{11} + P_{22}) A_1 \\ &\quad + \lambda E_2^T (P_{11} + P_{22}) A_2], \\ \tilde{\mathcal{H}}_{13} &= P_{22} B R^{-1} B^T P_{22}, \\ \tilde{\mathcal{H}}_{22} &= A^T P_{22} + P_{22} A - P_{22} B R^{-1} B^T P_{22} + Q + A_1^T (P_{11} \\ &\quad + P_{22}) A_1 + \lambda A_2^T (P_{11} + P_{22}) A_2 + [P_{22} E \\ &\quad + A_1^T (P_{11} + P_{22}) E_1 + \lambda A_2^T (P_{11} + P_{22}) E_2] M^{-1} \\ &\quad \times [E^T P_{22} + E_1^T (P_{11} + P_{22}) A_1 \\ &\quad + \lambda E_2^T (P_{11} + P_{22}) A_2], \\ \tilde{\mathcal{H}}_{23} &= -Q, \\ \tilde{\mathcal{H}}_{33} &= A_r^T P_{33} + P_{33} A_r + Q + P_{22} B R^{-1} B^T P_{22} + \frac{1}{\rho^2} \\ &\quad \cdot P_{33} P_{33}. \end{aligned} \quad (37)$$

Proposition 6. Suppose $P_{11} \in \mathcal{S}_+(\mathbb{R})$, $P_{22} \in \mathcal{S}_+(\mathbb{R})$, and $P_{33} \in \mathcal{S}_+(\mathbb{R})$ are the solution of the following block matrix inequality:

$$H := \begin{bmatrix} H_{11} & 0 & 0 & P_{11} E & 0 & P_{22} B \\ * & H_{22} & -Q & H_{24} & 0 & 0 \\ * & * & H_{33} & 0 & P_{33} & 0 \\ * & * & * & -M & 0 & 0 \\ * & * & * & * & -\rho^2 I & 0 \\ * & * & * & * & * & -R \end{bmatrix} \leq 0, \quad (38)$$

and

$$M < 0, \quad (39)$$

where

$$\begin{aligned}
 H_{11} &= A^T P_{11} + P_{11} A - \rho^2 C^T C, \\
 H_{22} &= A^T P_{22} + P_{22} A - P_{22} B R^{-1} B^T P_{22} + Q, \\
 H_{23} &= -Q, \\
 H_{24} &= P_{22} E + A_1^T (P_{11} + P_{22}) E_1 \\
 &\quad + \lambda A_2^T (P_{11} + P_{22}) E_2, \\
 H_{33} &= A_r^T P_{33} + P_{33} A_r + Q.
 \end{aligned} \tag{40}$$

Then $\tilde{P}$ with form of (31), $L = \rho^2 P_{11}^{-1} C^T$ and $K = -R^{-1} B^T P_{22}$ are the solutions of (24) and (25). Moreover, the H_∞ tracking control performance in (24) is guaranteed for a prescribed ρ^2 .

Proof. Applying the well-known Schur definiteness criterion to symmetric block matrix H , together with $L = \rho^2 P_{11}^{-1} C^T$ and $K = -R^{-1} B^T P_{22}$, it is easy to see that (38) is equivalent to (24). As far as the H_∞ tracking control performance in (24) is guaranteed, it can be directly obtained by Theorem 5. $\square$

Remark 7. In equation (32) and (37), if there exists $P_{11} > 0$ such that $\tilde{\mathcal{H}}_{11} \leq 0$, this implies

$$A^T P_{11} + P_{11} A - C^T L^T P_{11} - P_{11} L C \leq 0, \tag{41}$$

i.e.,

$$(A - LC)^T P_{11} + P_{11} (A - LC) \leq 0. \tag{42}$$

Thus, the following system

$$d\bar{e}(t) = (A - LC) \bar{e}(t) dt \tag{43}$$

is stable. Furthermore, if there exists $P_{11} > 0$ such that $\tilde{\mathcal{H}}_{11} < 0$, this implies

$$(A - LC)^T P_{11} + P_{11} (A - LC) < 0. \tag{44}$$

Therefore, system (43) is asymptotically stable; i.e., $A - LC$ is stable. In this paper, the estimation error system (17) can be seen as the extension of (43) where (17) presents the differences between $\hat{x}(t)$ and $x(t)$. Furthermore, in (38), $H_{11} < 0$; i.e.,

$$A^T P_{11} + P_{11} A - \rho^2 C^T C < 0, \tag{45}$$

and if $C = 0$, then A is stable. However, in general, $C \neq 0$; the matrix A is not necessarily stable.

4. Nonlinear Systems and Corresponding Fuzzy Systems

For nonlinear system as in the following forms

$$\begin{aligned}
 dx(t) &= [f(x(t)) + g(x(t))u(t) + E(x)w(t)] dt \\
 &\quad + [f_1(x(t)) + E_1(x)w(t)] dW_1(t) \\
 &\quad + [f_2(x(t)) + E_2(x)w(t)] dN_1(t), \\
 y(t) &= m(x(t)) + v, \quad i = 1, 2, \dots, r,
 \end{aligned} \tag{46}$$

the reference model is suggested as follows:

$$dx_r(t) = [f_r(x_r(t)) + r(t)] dt. \tag{47}$$

The observer is proposed to deal with the state estimation of system (46)

$$\begin{aligned}
 d\hat{x}(t) &= [f(\hat{x}(t)) + g(\hat{x}(t))u(t) \\
 &\quad + L(\hat{x})(y(t) - \hat{y}(t))] dt, \quad \hat{y}(t) = m(\hat{x}(t)).
 \end{aligned} \tag{48}$$

Let

$$e(t) = x(t) - \hat{x}(t), \tag{49}$$

and denote $\tilde{x} = [e^T, x^T, x_r^T]^T$, $\tilde{w} = [v^T, w^T, r^T]^T$. Design the control u with form of

$$u(t) = K(\tilde{x}(t)) [\hat{x}(t) - x_r(t)], \tag{50}$$

and then

$$\begin{aligned}
 d\tilde{x}(t) &= [\tilde{f}(\tilde{x}(t)) + \tilde{E}(\tilde{x}(t))\tilde{w}(t)] dt \\
 &\quad + [\tilde{f}_1(\tilde{x}(t)) + \tilde{E}_1(\tilde{x}(t))\tilde{w}(t)] dW_1(t) \\
 &\quad + [\tilde{f}_2(\tilde{x}(t)) + \tilde{E}_2(\tilde{x}(t))\tilde{w}(t)] dN_1(t),
 \end{aligned} \tag{51}$$

where

$$\begin{aligned}
 \tilde{f}(\tilde{x}) &= [(f(x) - f(\hat{x})) \\
 &\quad + (g(x) - g(\hat{x}))K(\hat{x})(\hat{x} - x_r) \\
 &\quad - L(\hat{x})(m(x) - m(\hat{x}))]^T, (f(x) \\
 &\quad + g(x)K(\hat{x})(\hat{x} - x_r))^T, f_r(x_r)^T]^T, \\
 \tilde{f}_1(\tilde{x}) &= [f_1(x)^T, f_1(x)^T, 0^T]^T, \\
 \tilde{f}_2(\tilde{x}) &= [f_2(x)^T, f_2(x)^T, 0^T]^T, \\
 \tilde{E}(\tilde{x}) &= \begin{bmatrix} -L(\hat{x}) & E(x) & 0 \\ 0 & E(x) & 0 \\ 0 & 0 & I \end{bmatrix}, \\
 \tilde{E}_1(\tilde{x}) &= \begin{bmatrix} 0 & E_1(x) & 0 \\ 0 & E_1(x) & 0 \\ 0 & 0 & 0 \end{bmatrix}, \\
 \tilde{E}_2(\tilde{x}) &= \begin{bmatrix} 0 & E_2(x) & 0 \\ 0 & E_2(x) & 0 \\ 0 & 0 & 0 \end{bmatrix}.
 \end{aligned} \tag{52}$$

For a positive function $\tilde{l}(\tilde{x})$, an auxiliary positive function $\tilde{V}$ is suggested. The H_∞ tracking performance considering the initial condition is given by

$$\begin{aligned}
 \int_0^{t_f} \mathbb{E} [\tilde{l}(\tilde{x}(t))] dt &\leq \tilde{V}(\tilde{x}(0)) \\
 &\quad + \rho^2 \int_0^{t_f} \mathbb{E} [\tilde{w}^T(t) \tilde{w}(t)] dt.
 \end{aligned} \tag{53}$$

Theorem 8. Suppose $\tilde{V} : \mathbb{R}^{3n} \rightarrow \mathbb{R}_+$, $K(\tilde{x})$, $L(\tilde{x})$ constitute the solution of the following Hamilton-Jacobi inequality:

$$\mathcal{H}_1(\tilde{V})(\tilde{x}) \leq 0, \quad (54)$$

$$\rho^2 I - \frac{1}{2} \tilde{E}_1^T \tilde{V}_{\tilde{x}\tilde{x}} \tilde{E}_1 - \frac{\lambda}{2} \tilde{E}_2^T S \tilde{E}_2 > 0, \quad (55)$$

where (variable $\tilde{x}$ is omitted)

$$\begin{aligned} \mathcal{H}_1(\tilde{V})(\tilde{x}) := & \tilde{V}_{\tilde{x}}^T (\tilde{f} + \lambda \tilde{f}_2) + \frac{1}{2} \tilde{f}_1^T \tilde{V}_{\tilde{x}\tilde{x}} \tilde{f}_1 + \frac{\lambda}{2} \tilde{f}_2^T S \tilde{f}_2 \\ & + \tilde{l} + \frac{1}{4} (\tilde{V}_{\tilde{x}}^T \tilde{E} + \tilde{f}_1^T \tilde{V}_{\tilde{x}\tilde{x}} \tilde{E}_1 + \lambda \tilde{V}_{\tilde{x}}^T \tilde{E}_2 + \lambda \tilde{f}_2^T S \tilde{E}_2) \\ & \times \left(\rho^2 I - \frac{1}{2} \tilde{E}_1^T \tilde{V}_{\tilde{x}\tilde{x}} \tilde{E}_1 - \frac{\lambda}{2} \tilde{E}_2^T S \tilde{E}_2 \right)^{-1} \\ & \cdot (\tilde{V}_{\tilde{x}}^T \tilde{E} + \tilde{f}_1^T \tilde{V}_{\tilde{x}\tilde{x}} \tilde{E}_1 + \lambda \tilde{V}_{\tilde{x}}^T \tilde{E}_2 + \lambda \tilde{f}_2^T S \tilde{E}_2)^T, \end{aligned} \quad (56)$$

and $S \in \mathcal{S}_+(\mathbb{R})$ is a fixed positive definite matrix with

$$\tilde{V}_{\tilde{x}\tilde{x}}(\tilde{x}) \leq S. \quad (57)$$

Then the H_∞ tracking control performance in (53) is guaranteed for a prescribed $\rho^2 > 0$.

Proof. Applying Itô's formula to $\tilde{V}(\tilde{x}(t))$, there exist

$$\begin{aligned} & \int_0^{t_f} \mathbb{E} [\tilde{l}(\tilde{x}(t))] dt \\ & = \tilde{V}(\tilde{x}_0) - \mathbb{E} [\tilde{V}(\tilde{x}_{t_f})] \\ & \quad + \rho^2 \int_0^{t_f} \mathbb{E} [\tilde{w}^T(t) \tilde{w}(t)] dt \\ & \quad + \int_0^{t_f} \mathbb{E} [\mathcal{H}_1(\tilde{V})(\tilde{x}(t)) - \|\tilde{w}(t) - \xi(t)\|_\Xi^2] dt, \end{aligned} \quad (58)$$

where

$$\begin{aligned} \Xi = & \rho^2 I - \frac{1}{2} \tilde{E}_1^T (\tilde{x}(t)) \tilde{V}_{\tilde{x}\tilde{x}} (\tilde{x}(t)) \tilde{E}_1 (\tilde{x}(t)) - \frac{\lambda}{2} \\ & \cdot \tilde{E}_2^T (\tilde{x}(t)) S \tilde{E}_2 (\tilde{x}(t)) \\ \xi(t) = & \frac{1}{2} \Xi^{-1} [\tilde{V}_{\tilde{x}}^T (\tilde{x}(t)) \tilde{E} (\tilde{x}(t)) \\ & + \tilde{f}_1^T (\tilde{x}(t)) \tilde{V}_{\tilde{x}\tilde{x}} (\tilde{x}(t)) \tilde{E}_1 (\tilde{x}(t)) \\ & + \lambda \tilde{V}_{\tilde{x}}^T (\tilde{x}(t)) \tilde{E}_2 (\tilde{x}(t)) + \lambda \tilde{f}_2^T (\tilde{x}(t)) S \tilde{E}_2 (\tilde{x}(t))]^T. \end{aligned} \quad (59)$$

Keeping in mind that $\tilde{V}$ is positive and applying (54), we prove that

$$\int_0^{t_f} \mathbb{E} [\tilde{l}(\tilde{x}(t))] dt \leq \rho^2 \int_0^{t_f} \mathbb{E} [\tilde{w}^T(t) \tilde{w}(t)] dt. \quad (60)$$

This ends the proof. $\square$

The nonlinear system (46), (47), (48), (50), and (51) can be described by T-S fuzzy model as follows.

Model Rule i

IF $\zeta(t)$ is M_{i1} , and $\dots$ and $\zeta_p(t)$ is M_{ip} , THEN

$$\begin{aligned} dx(t) = & [A^{(i)} x(t) + B^{(i)} u(t) + w(t)] dt \\ & + [A_1^{(i)} x(t) + w(t)] dW_1(t) \\ & + [A_2^{(i)} x(t) + w(t)] dN_1(t), \end{aligned} \quad (61)$$

$$y(t) = C^{(i)} x(t) + v, \quad i = 1, 2, \dots, r.$$

Corresponding reference model is suggested as follows:

$$dx_r(t) = [A_r^{(i)} x_r(t) + r(t)] dt, \quad (62)$$

where $\zeta(t) = (\zeta_1(t), \dots, \zeta_p(t))$ are the premise variables, M_{ij} is the fuzzy set, and r is the number of model rules.

The following observer is proposed to deal with the state estimation of fuzzy system (61)

$$\begin{aligned} d\hat{x}(t) = & [A^{(i)} \hat{x}(t) + B^{(i)} u(t) + L^{(i)} (y(t) - \hat{y}(t))] dt, \\ \hat{y}(t) = & C^{(i)} \hat{x}(t). \end{aligned} \quad (63)$$

Then the controller $u(t)$ has the form as

$$u(t) = K^{(i)} [\hat{x}(t) - x_r(t)]. \quad (64)$$

Let $\tilde{M}_{ij}(\zeta_j(t))$ be the grade of membership of $\zeta_j(t)$ in M_{ij} ; then the membership function of $\zeta(t)$ for the i 'th rule is

$$\mu_i(\zeta(t)) = \tilde{M}_{i1} \tilde{M}_{i2} \dots \tilde{M}_{ip} \geq 0, \quad (65)$$

with $\sum_{i=1}^r \mu_i(\zeta(t)) > 0$. The standard membership function is defined by

$$h_i(\zeta(t)) = \frac{\mu_i(\zeta(t))}{\sum_{i=1}^r \mu_i(\zeta(t))}. \quad (66)$$

Then the fuzzy system is inferred as

$$\begin{aligned} dx(t) = & \sum_{i=1}^r h_i(\zeta(t)) \{ [A^{(i)} x(t) + B^{(i)} u(t) + w(t)] dt \\ & + [A_1^{(i)} x(t) + w(t)] dW_1(t) \\ & + [A_2^{(i)} x(t) + w(t)] dN_1(t) \}, \end{aligned} \quad (67)$$

$$y(t) = \sum_{i=1}^r h_i(\zeta(t)) \{ C^{(i)} x(t) + v \},$$

and

$$\begin{aligned} d\hat{x}(t) = & \sum_{i=1}^r h_i(\zeta(t)) \\ & \cdot \{ [A^{(i)} \hat{x}(t) + B^{(i)} u(t) + L^{(i)} (y(t) - \hat{y}(t))] dt \}, \end{aligned} \quad (68)$$

$$\hat{y}(t) = \sum_{i=1}^r h_i(\zeta(t)) \{ C^{(i)} \hat{x}(t) \},$$

with estimation errors

$$\begin{aligned}
 de(t) = & \sum_{i=1}^r h_i(\zeta(t)) \\
 & \cdot \left\{ \left[A^{(i)} e(t) - L^{(i)} (y(t) - \hat{y}(t)) + w(t) \right] dt \right. \\
 & + \left[A_1^{(i)} x(t) + w(t) \right] dW_1(t) \\
 & \left. + \left[A_2^{(i)} x(t) + w(t) \right] dN_1(t) \right\}. \quad (69)
 \end{aligned}$$

Then the controller $u(t)$ has the form as

$$u(t) = \sum_{i=1}^r h_i(\zeta(t)) \left\{ K^{(i)} [\hat{x}(t) - x_r(t)] \right\}. \quad (70)$$

and

$$\begin{aligned}
 l(e_r(t), u(t)) \\
 = \sum_{i=1}^r h_i(\zeta(t)) \left\{ e_r^T(t) Q^{(i)} e_r(t) + u^T(t) R^{(i)} u(t) \right\}. \quad (71)
 \end{aligned}$$

5. Simulation Examples

As the application of tracking system, the air-to-air missile pursuit systems are discussed, which are used to shot down escaping target such as aircraft, fighter, or missile [34, 35]. The relative dynamic motion between a homing-missile and the escaping target is described by the following system driven by both Wiener process and Poisson process.

$$\begin{aligned}
 dx_1(t) &= x_2(t) dt + c_1 x_2(t) dW(t), \\
 dx_2(t) &= \left[\frac{x_3^2(t)}{x_1(t)} + u_1(t) + v_1(t) \right] dt \\
 &\quad + \left[c_2 \frac{x_3^2(t)}{x_1(t)} + v_1(t) \right] dW(t), \\
 dx_3(t) &= \left[-\frac{x_2(t) x_3(t)}{x_1(t)} + u_2(t) + v_2(t) \right] dt \\
 &\quad + \left[c_3 \frac{x_2(t) x_3(t)}{x_1(t)} + v_2(t) \right] dW(t) \\
 &\quad + \left[c_4 \frac{x_3(t)}{x_1(t)} + v_2(t) \right] dN(t), \\
 y(t) &= \begin{bmatrix} x_1(t) \\ x_3(t) \end{bmatrix}, \quad x(0) = x_0 \in D, \quad t \in [0, t_f].
 \end{aligned} \quad (72)$$

Here $x(t) = (x_1(t), x_2(t), x_3(t))^T$ is the system state which describes the trajectory of missile, concretely; $x_1(t)$ is the relative distance between the missile and target; see Figure 1; $x_2(t)$ is the radial relative velocity; $x_3(t)$ is the tangential relative velocity; see Figure 2; and $u(t) = (u_1(t), u_2(t))^T$ is the input control with u_1 and u_2 being the missiles acceleration components along the x_1 and x_2 axes. $W(t)$ denotes the

FIGURE 1: Pursuit guidance course at time $t_0 < t_1 < t_2 < t_f$.

FIGURE 2: The geometric relationship between the target and missile.

continuous noise of the system such as the air friction caused by air resistance and the inner thermal noise caused by missile operating system. Poisson process $N(t)$ denotes the sudden discrete noise of the system such as directional trimming, or deceptive behavior of the missile to avoid being shot down by shooting out gas from two side jets. $y(t)$ is the measurement and t_f is the fighting time which denotes the missile's effective working time, and $C = [1 \ 0 \ 1]^T$.

Take $t_f = 25(\text{sec})$, $x_1(0) = 7875(\text{m})$, $x_2(0) = -343(\text{m/s})$, $x_3(0) = -10(\text{rad/s})$, $c_1 = c_2 = c_3 = 0.11$, $c_4 = 0.3$, $Q = \text{diag}(0, 1, 1) \times 10^{-2}$, $R = I_2$, and the density of Poisson jump $N(t)$ is 0.02; i.e., $\lambda = 0.02$, $\rho^2 = 0.49$, and

$$\begin{aligned}
 E &= E_1 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \times 10^{-3}, \\
 E_2 &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \times 10^{-3}. \quad (73)
 \end{aligned}$$

Let $r(t)$ the trajectory of the target's motion which is embedded in a reference model as follows:

$$\begin{aligned} dx_r &= [A_r x_r + r(t)] dt, \\ x_r(0) &= x_0, \end{aligned} \quad (74)$$

where $A_r = -I_3$ which implies the steady state $x_r(t) = r(t)$. Let $r(t)$ be the reference trajectories with

$$r(t) = \begin{bmatrix} t^2 - 362.6t + 7987.6 \\ 1.3t^2 - 24.1t - 274.4 \\ -0.9t^2 + 0.0149t - 0.0509 \end{bmatrix}, \quad (75)$$

$$t \in [0, 25],$$

$$d\hat{x}_1(t) = [\hat{x}_2(t) + L_1(y(t) - \hat{y}(t))] dt,$$

$$d\hat{x}_2(t) = \frac{\hat{x}_3^2(t)}{\hat{x}_1(t)} dt, \quad (76)$$

$$d\hat{x}_3(t) = -\frac{\hat{x}_2(t) \hat{x}_3(t)}{\hat{x}_1(t)} dt,$$

$$\hat{y}(t) = \hat{x}_1(t), \quad t \in [0, t_f].$$

Choose the fuzzy variable $\zeta = x_3/x_1$ and the fuzzy rules as follows:

Rule 1 (ζ about -0.45).

$$\begin{aligned} A^{(1)} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -0.45 \\ 0 & 0.45 & 0 \end{bmatrix}, \\ A_1^{(1)} &= \begin{bmatrix} 0 & 0.3 & 0 \\ 0 & 0 & -0.135 \\ 0 & 0.135 & 0 \end{bmatrix}, \\ A_2^{(1)} &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0.135 & 0 \end{bmatrix}, \\ P_1^{(1)} &= \begin{bmatrix} 0.3564 & -1.584 & -0.792 \\ -1.584 & 7.4571 & 1.76 \\ -0.792 & 1.76 & 9.2171 \end{bmatrix}, \\ P_2^{(1)} &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.43 & 0 \\ 0 & 0 & 0.43 \end{bmatrix}, \\ P_3^{(1)} &= \begin{bmatrix} 0.49 & 0 & 0 \\ 0 & 0.49 & 0 \\ 0 & 0 & 0.49 \end{bmatrix} \end{aligned} \quad (77)$$

Rule 2 (ζ about -0.3).

$$\begin{aligned} A^{(2)} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -0.3 \\ 0 & 0.3 & 0 \end{bmatrix}, \\ A_1^{(2)} &= \begin{bmatrix} 0 & 0.3 & 0 \\ 0 & 0 & -0.09 \\ 0 & 0.09 & 0 \end{bmatrix}, \\ A_2^{(2)} &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.09 & 0 \end{bmatrix}, \\ P_1^{(2)} &= \begin{bmatrix} 0.2376 & -1.584 & -0.792 \\ -1.584 & 11.1857 & 2.64 \\ -0.792 & 2.64 & 13.8257 \end{bmatrix}, \\ P_2^{(2)} &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.35 & 0 \\ 0 & 0 & 0.35 \end{bmatrix}, \\ P_3^{(2)} &= \begin{bmatrix} 0.49 & 0 & 0 \\ 0 & 0.49 & 0 \\ 0 & 0 & 0.49 \end{bmatrix} \end{aligned} \quad (78)$$

Rule 3 (ζ about -0.15).

$$\begin{aligned} A^{(3)} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -0.15 \\ 0 & 0.15 & 0 \end{bmatrix}, \\ A_1^{(3)} &= \begin{bmatrix} 0 & 0.3 & 0 \\ 0 & 0 & -0.045 \\ 0 & 0.045 & 0 \end{bmatrix}, \\ A_2^{(3)} &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.045 & 0 \end{bmatrix}, \\ P_1^{(3)} &= \begin{bmatrix} 0.1188 & -1.584 & -0.792 \\ -1.584 & 22.3714 & 5.28 \\ -0.792 & 5.28 & 27.6514 \end{bmatrix}, \\ P_2^{(3)} &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 0.25 \end{bmatrix}, \\ P_3^{(3)} &= \begin{bmatrix} 0.49 & 0 & 0 \\ 0 & 0.49 & 0 \\ 0 & 0 & 0.49 \end{bmatrix} \end{aligned} \quad (79)$$

Rule 4 (ζ about -0.07).

$$A^{(4)} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -0.07 \\ 0 & 0.07 & 0 \end{bmatrix},$$

$$A_1^{(4)} = \begin{bmatrix} 0 & 0.3 & 0 \\ 0 & 0 & -0.021 \\ 0 & 0.021 & 0 \end{bmatrix}$$

$$A_2^{(4)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.021 & 0 \end{bmatrix},$$

$$P_1^{(4)} = \begin{bmatrix} 0.055468 & -1.5848 & -0.7924 \\ -1.5848 & 47.9628 & 11.32 \\ -0.7924 & 11.32 & 59.2828 \end{bmatrix},$$

$$P_2^{(4)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.17 & 0 \\ 0 & 0 & 0.17 \end{bmatrix},$$

$$P_3^{(4)} = \begin{bmatrix} 0.49 & 0 & 0 \\ 0 & 0.49 & 0 \\ 0 & 0 & 0.49 \end{bmatrix}$$

Rule 5 (ζ about -0.04).

$$A^{(5)} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -0.04 \\ 0 & 0.04 & 0 \end{bmatrix},$$

$$A_1^{(5)} = \begin{bmatrix} 0 & 0.3 & 0 \\ 0 & 0 & -0.012 \\ 0 & 0.012 & 0 \end{bmatrix}$$

$$A_2^{(5)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.012 & 0 \end{bmatrix}$$

$$P_1^{(5)} = \begin{bmatrix} 0.031712 & -1.5856 & -0.7928 \\ -1.5856 & 83.9773 & 19.82 \\ -0.7928 & 19.82 & 103.7973 \end{bmatrix},$$

$$P_2^{(5)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.13 & 0 \\ 0 & 0 & 0.13 \end{bmatrix},$$

$$P_3^{(5)} = \begin{bmatrix} 0.49 & 0 & 0 \\ 0 & 0.49 & 0 \\ 0 & 0 & 0.49 \end{bmatrix}$$

Rule 6 (ζ about -0.012).

$$A^{(6)} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -0.012 \\ 0 & 0.012 & 0 \end{bmatrix}$$

$$A_1^{(6)} = \begin{bmatrix} 0 & 0.3 & 0 \\ 0 & 0 & -0.0036 \\ 0 & 0.0036 & 0 \end{bmatrix},$$

$$A_2^{(6)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.0036 & 0 \end{bmatrix}$$

$$P_1^{(6)} = \begin{bmatrix} 0.0095126 & -1.5854 & -0.79272 \\ -1.5854 & 279.8962 & 66.06 \\ -0.79272 & 66.06 & 345.9562 \end{bmatrix},$$

$$P_2^{(6)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.07 & 0 \\ 0 & 0 & 0.07 \end{bmatrix},$$

$$P_3^{(6)} = \begin{bmatrix} 0.49 & 0 & 0 \\ 0 & 0.49 & 0 \\ 0 & 0 & 0.49 \end{bmatrix}$$

Rule 7 (ζ about -0.008).

$$A^{(7)} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -0.008 \\ 0 & 0.008 & 0 \end{bmatrix}$$

$$A_1^{(7)} = \begin{bmatrix} 0 & 0.3 & 0 \\ 0 & 0 & -0.0024 \\ 0 & 0.0024 & 0 \end{bmatrix},$$

$$A_2^{(7)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0.0024 & 0 \end{bmatrix}$$

$$P_1^{(7)} = \begin{bmatrix} 0.0063424 & -1.5856 & -0.7928 \\ -1.5856 & 419.8867 & 99.1 \\ -0.7928 & 99.1 & 518.9867 \end{bmatrix},$$

$$P_2^{(7)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0.06 & 0 \\ 0 & 0 & 0.06 \end{bmatrix},$$

$$P_3^{(7)} = \begin{bmatrix} 0.49 & 0 & 0 \\ 0 & 0.49 & 0 \\ 0 & 0 & 0.49 \end{bmatrix}.$$

(80)

(82)

(81)

(83)

Remark 9. We find that, in the fuzzy rules, the coefficients of $A^{(i)}$ have the form with

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -b \\ 0 & b & 0 \end{bmatrix}, \quad (84)$$

where $b > 0$. For every rule i , P_{11} , P_{22} , and P_{33} are solved by the following steps:

Step 1. Solve $P_{11}^* > 0$ such that

$$P_{11}^* = \arg \max_{P_{11} > 0} \alpha \quad (85)$$

subject to

$$A^T P_{11} + P_{11} A - \rho^2 C^T C \leq -\alpha I, \quad (86)$$

$$\alpha > 0. \quad (87)$$

The above optimal P_{11}^* could be solved by increasing α until P_{11} cannot be found in LMIs (86) and (87).

Step 2. Fix $P_{11} = P_{11}^*$ solved by Step 1. Suppose P_{22} has the form of

$$P_{22} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & p & q \\ 0 & q & p \end{bmatrix}, \quad (88)$$

where $p > 0, q \geq 0$. Solve p, q such that

$$\tilde{\mathcal{H}}_2 := \begin{bmatrix} \tilde{\mathcal{H}}_{11} & \tilde{\mathcal{H}}_{12} \\ * & \tilde{\mathcal{H}}_{22} \end{bmatrix} \leq 0, \quad (89)$$

where $\tilde{\mathcal{H}}_{ij}$ is determined by (37), $i, j = 1, 2$. Under the conditions of $p > 0, p^2 > q^2$, for a fixed q , P_{22} can be solved by increasing p until matrix inequality (89) can be true.

Step 3. Fix P_{11} and P_{22} which are determined by Steps 1 and 2. The positive definite matrix $P_{33} > 0$ can be obtained by solving the LMIs (38) in which P_{11} and P_{22} are fixed matrices.

The weighted function $h_i(\zeta)$ is given by

$$h_1(\zeta) = \begin{cases} 1 - \frac{\zeta - \zeta_1}{\zeta_2 - \zeta_1}, & \zeta_1 \leq \zeta < \zeta_2 \\ 1, & \zeta < \zeta_1 \\ 0, & \text{others} \end{cases} \quad (90)$$

$$h_i(\zeta) = \begin{cases} 1 - \frac{\zeta - \zeta_i}{\zeta_{i+1} - \zeta_i}, & \zeta_i \leq \zeta < \zeta_{i+1} \\ 1 - \frac{\zeta_i - \zeta}{\zeta_i - \zeta_{i-1}}, & \zeta_{i-1} \leq \zeta < \zeta_i \\ 0, & \text{others} \end{cases} \quad (91)$$

$$h_7(\zeta) = \begin{cases} 1 - \frac{\zeta - \zeta_6}{\zeta_7 - \zeta_6}, & \zeta_6 \leq \zeta < \zeta_7 \\ 1, & \zeta_7 \leq \zeta \\ 0, & \text{others} \end{cases} \quad (92)$$

FIGURE 3: Fuzzy rules based on weighted functions $h_i(\zeta)$ defined by (90)–(92).

FIGURE 4: The sample trajectories of the fuzzy system (67) with coefficient matrices provided by Rules 1–7 and the original system (72).

where $\zeta_1 = -0.45, \zeta_2 = -0.07, \zeta_3 = -0.012, \zeta_4 = -0.008, i = 2, 3, 4, 5, 6$. Figure 3 shows the profiles of $h_i(\zeta), i = 1, 2, \dots, 7$.

Figure 4 shows the sample trajectories of the original system (72) and the corresponding fuzzy system (67) with $u = 0$ and $v = 0$. This illustrates that the T-S fuzzy method can be used to approximate the stochastic nonlinear systems via the fuzzy systems with proper coefficients given by Rule $i, i = 1, 2, \dots, 7$.

FIGURE 5: The sample trajectories of fuzzy control $u_1(t)$, $u_2(t)$ for fuzzy system (67) with coefficient matrices provided by Rules 1–7 corresponding to nonlinear system (72) under Poisson process.

By (70), the H_∞ tracking fuzzy control $u(t) = [u_1(t), u_2(t)]^T$ is obtained by

$$u(t) = \sum_{i=1}^7 h_i(\zeta(t)) \{K^{(i)} [\hat{x}(t) - x_r(t)]\}. \quad (93)$$

Here $K^{(i)} = -P_{22}^{(i)}$, $i = 1, 2, \dots, 7$. Figure 5 illustrates the sample trajectories of fuzzy control $u(t)$ for system (72) with Poisson process. It shows that the values of control change violently when Poisson jumps occur.

Figures 6, 7, and 8 show the sample trajectories of the components of the state $x(t)$, the reference $x_r(t)$, and the estimation state $\hat{x}(t)$. These show that, under the proposed H_∞ tracking fuzzy control (93), the state $x(t)$ and its estimation $\hat{x}(t)$ of fuzzy system (67) with coefficient matrices provided by Rules 1–7 corresponding to (72) take values around the reference trajectory $x_r(t)$. Figure 9 shows the estimation error $|e(t)|^2 = |x(t) - \hat{x}(t)|^2$ which illustrates the performance difference between the state estimation $\hat{x}(t)$ and the state $x(t)$. The four figures confirm that the control defined by (93) can achieve the desired performance (53) with $\tilde{l}(\bar{x}(t)) = l(e_r(t), u(t))$, where $l(e_r(t), u(t))$ is defined by (71).

Now, we compare our results with that in [35]. In [35], the guidance law uses the information for the target acceleration bound, and the guidance command is derived based on the nonlinear planar engagement kinematics. In our guidance law design, we consider the nonlinear model of the system with fuzzy method. Some comparisons are given as follows:

(1) In the control algorithm of [35], the sliding mode control scheme is used to obtain the guidance law. In our control design, an adaptive fuzzy scheme is employed to

FIGURE 6: The sample trajectories of $x_1(t)$ and $x_{r1}(t)$ of fuzzy system (67) with coefficient matrices provided by Rules 1–7 under fuzzy control (93) corresponding to nonlinear system (72).

FIGURE 7: Trajectories of $x_2(t)$ and $x_{r2}(t)$ of fuzzy system (67) with coefficient matrices provided by Rules 1–7 under fuzzy control (93) corresponding to nonlinear system (72).

cancel the exogenous disturbance $v(t)$ in the stochastic system with Brownian motion and Poisson jumps.

(2) The controller obtained in [35] is based on solving a nonlinear function $V(x)$. In our paper, the robust tracking controller is given with fuzzy forms in (70) which is only based on the locally linear approximation.

(3) The controller in [35] depends on the sliding surface and the state. Our controller $u(t)$ in (70) depends on the difference between the state $x(t)$ and the reference trajectory $x_r(t)$ and the estimation errors $e(t)$.

FIGURE 8: Trajectories of $x_3(t)$ and $x_{r3}(t)$ of fuzzy system (67) with coefficient matrices provided by Rules 1–7 under fuzzy control (93) corresponding to nonlinear system (72).

FIGURE 9: The estimation errors $|e(t)|^2$ of fuzzy system (67) with coefficient matrices provided by Rules 1–7 under fuzzy control (93) corresponding to nonlinear system (72).

6. Conclusion

The H_∞ tracking control technique combining with adaptive control algorithm and T-S fuzzy method has been studied to design the H_∞ tracking control to achieve the desired performance for nonlinear stochastic systems driven by both Brownian motion and Poisson jumps. By using adaptive fuzzy control algorithms, the corresponding adaptive fuzzy control laws are derived, which have been employed to treat the H_∞ design problem. A real-world example is used to show the effectiveness of the proposed method. Simulation results illustrate that the proposed adaptive T-S fuzzy control algorithms are practically useful to achieve the H_∞ tracking performance.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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