Extended Dissipative Control for Markovian Jump Time-Delayed Systems with Bounded Disturbances

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In this work, the result of reachable set bounding and extended dissipative control synthesis of the Markovian jump time-delayed system is studied subject to stochastic actuator failures and partially known transition probabilities. Specifically, a novel actuator fault model is designed, in which the actuator fault matrix satisfies a certain probabilistic condition. Under the construction of an appropriate Lyapunov–Krasovskii functional (LKF), as well as reciprocal convex approach, Jensen’s integral inequality, and reachable set lemma, delay-dependent sufficient criteria are obtained in terms of linear matrix inequalities (LMIs) for finding an ellipsoid to bound the reachable sets of the Markovian jump time-delayed system with bounded disturbances. Finally, two numerical examples are provided to validate the effectiveness of the proposed strategy.

1. Introduction

Markovian jump systems are a kind of stochastic switched systems, in which the switching between multiple modes is governed by a stochastic process described by a Markov chain. Furthermore, Markovian jump systems are appropriate model systems with random abrupt variations, which may be due to malfunction of machine in manufacturing systems, fluctuations in operating points, and environmental disturbances [1–5]. Therefore, a remarkable progress has been made in the study of Markovian jump systems and has proved its successful applications in chemical systems, economic systems, power systems, electrical circuit systems, and so on [6–9]. A new feedback controller is designed in [10] to ensure the finite-time mean square stability of the nonlinear Markovian jump systems, in which the nonlinear element satisfies the prescribed conic sector condition. Very recently, the problem of model reduction for nonhomogeneous Markovian jump systems is studied in [11], in which asynchronization is designed by a hidden Markov model with Markovian jump parameters. Xia et al. [12] reported the result of the dissipative sampled-data scheme for fuzzy Markovian jump systems. However, it is mentioned that the abovementioned studies are based on a particular ideal assumption that the information of each element in the transition probabilities matrix is available. In fact, it is hard to measure or determine the knowledge of all the elements, which motivates further study on Markovian jump systems with partly known transition probabilities that are more general [13–15].

It is known that reachable set estimation is used to find an appropriate domain, which can bound all the reachable states of a dynamical system with respect to input disturbances and zero initial conditions. During the past few years, reachable set estimation of dynamical systems has various practical applications in aircraft collision avoidance, peak-to-peak gain minimization, and control synthesis. Therefore, it is necessary to study the problem of reachable set estimation with time-delay dynamical systems, and a great number of results have been paid much attention in past few years [16–18]. For instance, the problem of reachable set...
estimation of singular systems is studied subjected to time delay and bounded peak inputs [19]. Based on the novel LKF approach, sufficient conditions are derived in terms of LMIs to ensure the reachable set of the linear systems bounded in [20]. Feng et al. [21] reported the reachable set estimation of discrete-time fuzzy systems subjected to time delay and external disturbance.

In practical control systems, there often exist faults due to the reasons of actuators aging, zero shift, electromagnetic interference, and nonlinear amplification in different frequency field. During the system operation, faults may affect the sensors, the actuators, and the system components, which may lead to intolerable performance of the closed-loop dynamical system. Therefore, from a safety as well as performance point of view, it is required to design a fault-tolerant controller, which can tolerate actuator or sensor faults and guarantee the stability and performance of resulting closed-loop systems [22–25]. For example [26], a fuzzy-based fault-tolerant control approach is designed for nontriangular nonlinear systems with respect to immeasurable states and actuator failures. Sun et al. [27] studied the composite reliable control problem for stochastic systems with disturbance observer. Based on the Lyapunov–Krasovskii functional together with partially known transition conditions, a new set of sufficient condition is derived in [28] for the nonlinear time-delay systems subjected to random fluctuations.

On the other side, the concept of extended dissipative was firstly considered in [29] where some well-known performance indices, namely, \( H_{\infty} \), performance, passivity performance, mixed \( H_{\infty} \) passivity performance, \( L_2 - L_\infty \) performance, and \((Q, S, R)\)-dissipative performance can be obtained by adjusting weighting matrices of extended dissipative [29–31]. Very recently, the concept of extended dissipative has been effectively applied to several dynamical systems in reports [32–34]. Zhu et al. [35] reported the problem of finite-time extended dissipative-based control of neutral switched systems with stochastic actuator failures. Under the extended dissipative analysis with an average dwell-time approach, an explicit expression of the desired Markov switching estimator is presented in [36]. To the best of authors’ knowledge, the extended dissipative concept together with reachable set estimation has not been applied to Markovian jump time-delayed systems subjected to probabilistic faults yet in the existing literatures, which motivates our present study. The main notable contributions of this paper can be highlighted as follows:

(i) The concept of extended dissipative and reachable set estimation is successfully first time applied to Markovian jump time-delayed systems with partially known transition probabilities and bounded disturbances

(ii) We have investigated the result of the extended dissipative analysis and stochastic fault-tolerant control design for a class of Markovian jump systems where the transition rate matrix satisfies the partially known probability conditions

(iii) Under the appropriate LKF, Jensen’s integral inequality and the reciprocal convex approach, a new set of sufficient conditions is obtained in the form of LMIs to guarantee the Markovian jump time-delayed system bounded by an ellipsoid and satisfies the extended dissipative performance index

(iv) Two numerical simulation demonstrate the feasibility and effectiveness of the proposed approach

The remaining part of this work is constructed as follows. The system description and problem formulation are provided in Section 2. The main results on extended dissipative-based stochastic fault-tolerant control for Markovian jump time-delayed systems with partially known transition probabilities and bounded disturbance are given in Section 3. Two examples are presented in Section 4 to demonstrate the effectiveness and feasibility of the obtained results. Finally, conclusions and the direction of future research are made in Section 5.

### Notations

1. The superscripts “\( T \)” and “\((-1)\)” stand for matrix transposition and matrix inverse, respectively; \( \mathbb{R}^n \) and \( \mathbb{R}^{m \times n} \) denote the \( n \)-dimensional Euclidean space and the set of all \( n \times m \) real matrices, respectively; the notation \( P > 0 \) \((\geq 0)\) means that \( P \) is real, symmetric, and positive definite (positive semi-definite); \( I \) is the identity matrix of appropriate dimension; the notation \( E[\cdot] \) stands for the expectation operator; and “\(" \)” is used to represent a term that is induced by symmetry.

### 2. Problem Formulation and Preliminaries

Consider the following Markovian jump systems with time-varying delay defined on a complete probability space \((\Omega, \mathcal{F}, \mathbb{P})\) and described as follows:

\[
\begin{align*}
\dot{x}(t) &= A(r_t)x(t) + A_d(r_t)x(t - d(t)) + B(r_t)u^f(r_t)(t) \\
&\quad + D(r_t)\omega(t), \\
z(t) &= C_1(r_t)x(t) + C_2(r_t)\omega(t), \\
x(t) &= \phi(t), \quad t \in [-d, 0],
\end{align*}
\]

(1)

where \( x(t) \in \mathbb{R}^n \) is the state vector; \( u^f(r_t) \in \mathbb{R}^m \) is the control input with respect to actuator fault; \( \omega(t) \in \mathbb{R}^q \) is the disturbance; \( z(t) \) represents system output; \( \phi(t) \) is the initial condition of the state; and \( \{r_t, t \geq 0\} \) is the Markov process and takes values in a finite set \( \mathbb{N} = \{1, 2, \ldots, n\} \), and it satisfies the following transition probability conditions:

\[
\text{Prob}(r_{t+\Delta t} = j | r(t) = i) = \begin{cases} 
\pi_{ij} \Delta t + o(\Delta t), & \text{if } i \neq j, \\
1 + \pi_{ii} \Delta t + o(\Delta t), & \text{if } i = j,
\end{cases}
\]

(2)

where \( \Delta(t) > 0 \) and \( \lim_{t \to \infty} O(\Delta(t))/\Delta(t) = 0; \pi_{ij} \geq 0 \) is the transition rate from mode \( j \) at time \( t \) to mode \( j \) at time \( t + \Delta(t) \) if \( i \neq j \) and \( \pi_{ii} = \sum_{j \neq i} \pi_{ij} \); the matrices \( A(r_t), A_d(r_t), B(r_t), D(r_t), C_1(r_t), \) and \( C_2(r_t) \) are known matrices of compatible dimensions. The set \( \mathbb{N} \) comprises the various operation modes of system (1), and for each possible value of
For a positive-definite symmetric matrix $P_i > 0$, we define an ellipsoid $\epsilon(P_i)$ bounding the reachable set (7) as follows:

$$
\epsilon(P_i) = \{x(t) \in \mathbb{R}^n \mid x(t) \text{ and } \omega(t) \text{ satisfy } (1) \text{ and } (4)\}. 
$$

We consider the following static feedback controller for system (1):

$$
u_i(t) = K_i x(t),
$$
in which $K_i$ represent the controller gain matrices to be determined. Then, the following stochastic fault model is adopted for this study:

$$
u_i(t) = \Xi u_i(t),
$$
where $\Xi = \text{diag}[\xi_1, \ldots, \xi_m]$ with $\xi_j$ ($j = 1, \ldots, m$) are the $m$ unrelated random variables. It is assumed that $\xi_j$ is with mathematical expectation $\mu_j$ and variance $\sigma_j^2$, respectively, and $H_j = \text{diag}\left\{0, 0, \ldots, 0, 1, 0, \ldots, 0\right\}_{m-j}$.

Also, we define $\Xi = \text{diag}[\mu_1, \ldots, \mu_m]$ and $\Delta = \text{diag}[\sigma_1, \ldots, \sigma_m]$.

Combining (1) and (10), we obtain the following closed-loop systems:

$$
\dot{x}(t) = (A_i + B_i \Xi K_j)x(t) + B_i(\Xi - \Xi)K_j x(t) + A_{ij} x(t - \tau(t)) + D_i \omega(t),
$$

$$
z(t) = C_i x(t) + C_{2i} \omega(t).
$$

Our main aim of this study is to derive an ellipsoid $\zeta$, as small as possible, that bounds the reachable set $\mathcal{R}_e$ of system (1) subject to time-varying delays and bounded disturbances (4). Then, we will design a stochastic fault-tolerant controller (10), such that the reachable set of the closed-loop system (11) is bounded and extended dissipative by a given ellipsoid $\epsilon(P_i)$. Before proving our main results, the following lemmas, assumption, and definition are introduced.

**Lemma 1** (see [35]). For any symmetric positive definite matrix $H \in \mathbb{R}^{m \times n}$ and a scalar $h > 0$, such that the following integrations are well-defined, then

$$
h \int_{t-h}^{t} x^T(s) H x(s) ds \geq \int_{t-h}^{t} x(s) ds^T H \int_{t-h}^{t} x^T(s). 
$$

**Lemma 2** (see [35]). Given appropriate dimensioned matrices $S_{11}$, $S_{12}$, and $S_{22}$ with $S_{11}^T = S_{11}$, $S_{22}^T = S_{22}$, then the inequality $S_{11} + S_{12}^T S^{-1}_{22} S_{12} \leq 0$ holds if and only if $S_{11} > S_{12}^T S^{-1}_{22} S_{12} \leq 0$. Otherwise, the reciprocall convex combination of $f_i$ over $D$ satisfies

$$
\min_{\alpha_i \geq 0, \sum \alpha_i = 1} \sum \alpha_i f_i(t) = \sum f_i(t) + \max_{\gamma(t)} \sum \alpha_i g_i(t),
$$

subjected to

$$
\left\{ g_i(t) : \mathbb{R}^m \to \mathbb{R}, g_{ij}(t) = g_{ij}(t), \left| \left| g_{ij}(t) \right| \right| \leq 0 \right\}. 
$$

**Lemma 3** (see [18]). Let $f_1, f_2, \ldots, f_N : \mathbb{R}^m \to \mathbb{R}$ have positive values in an open subset $D$ of $\mathbb{R}^m$. Then, the reciprocally convex combination of $f_i$ over $D$ satisfies

$$
\min_{\alpha_i \geq 0, \sum \alpha_i = 1} \sum \alpha_i f_i(t) = \sum f_i(t) + \max_{\gamma(t)} \sum \alpha_i g_i(t),
$$

subjected to

$$
\left\{ g_{ij} : \mathbb{R}^m \to \mathbb{R}, g_{ij}(t) = g_{ij}(t), \left| \left| g_{ij}(t) \right| \right| \leq 0 \right\}. 
$$

**Definition 1** (see [35]). For given matrices $\Phi_1, \Phi_2, \Phi_3,$ and $\Phi_4$, the considered closed-loop system (8) is said to be the extended dissipative if there exists a scalar $\rho$ such that the
upcoming inequality holds for all $T_f \geq 0$ and $w(t) \in \mathcal{L}_2[0, \infty)$:

$$\mathbb{E}\left\{ \int_0^{T_f} \mathcal{L}(t) \, dt \right\} \geq \sup_{0 \leq t \leq T_f} \mathbb{E}\{ z^T(t) \Phi_z z(t) \} \geq \rho, \quad (15)$$

where $\mathcal{L}(t) = [z^T(t) \Phi_z z(t) + 2z^T(t) \Phi_z w(t) + w^T(t) \Phi_z w(t)]$.

### 3. Main Results

In this section, the first reachable set estimation problem for Markovian jump time-delayed systems with partially known transition probabilities is considered based on Jensen’s integral equality, novel reachable set lemma, and improved reciprocally convex combination method. Next, under extended dissipative performance index, a novel stochastic fault-tolerant controller is proposed and a sufficient condition is given.

**Theorem 1.** For any given scalars $d \geq 0$, $\mu$, $\mu_0$, $\sigma_j (j = 1, \ldots, m)$, $\bar{w}$, and the matrix $K_j$, if there exists appropriately dimensioned matrices $P > 0$, $Q > 0$, $Q > 0$, $R > 0$, $S, M > 0$, and $N > 0$, symmetric matrices $E$, $E_1$, $W$, and $Z$, and a scalar $\alpha > 0$, the following LMIs hold for $i \in \mathbb{N}$:

$$\Theta_i = \begin{bmatrix} \Theta_{6,6} & \mathcal{A}_i^T & \mathcal{H}_i^T N \\ * & -d^2 N^{-1} & 0 \\ * & * & -\mathcal{H}^{-1} \end{bmatrix} < 0, \quad (16)$$

$$\sum_{j \in \mathcal{T}_i} \pi_{ij} e^{-\alpha d} (Q_j - Z_i) \leq 0, \quad (17)$$

$$P_j - W_i \leq 0, \quad j \in T^{\uparrow}_{\text{sk}}, j \neq i, \quad (18)$$

$$e^{-\alpha d} (Q_j - Z_i) \leq 0, \quad j \in T^{\uparrow}_{\text{sk}}, j \neq i, \quad (19)$$

$$P_j - W_i \geq 0, \quad j \in T^{\downarrow}_{\text{sk}}, j = i, \quad (20)$$

$$Q_j - Z_i \geq 0, \quad j \in T^{\downarrow}_{\text{sk}}, j = i, \quad (21)$$

$$\begin{bmatrix} M & E \\ * & M \end{bmatrix} \geq 0, \quad \begin{bmatrix} N & E_1 \\ * & N \end{bmatrix} \geq 0, \quad (22)$$

where

$$\Theta_{1,1} = 2P_i (A_i + B_i \Sigma K_j) + \sum_{j \in \mathcal{T}_i} \pi_{ij} [P_j - W_i] + S + \alpha P_i + Q_i + R + dM - e^{-\alpha d} N,$$

$$\Theta_{1,2} = P_i A_i + e^{-\alpha d} (N - E_1),$$

$$\Theta_{1,3} = e^{-\alpha d} E_1,$$

$$\Theta_{1,6} = P_i D_i,$$

$$\Theta_{2,2} = e^{-\alpha d} [(1 - \mu)S + E_1 + E_1^T - 2N],$$

$$\Theta_{2,3} = e^{-\alpha d} (N - E_1),$$

$$\Theta_{3,3} = e^{-\alpha d} [R + Q_i + N],$$

$$\Theta_{4,4} = \frac{e^{-\alpha d}}{d} M,$$

$$\Theta_{4,5} = \frac{e^{-\alpha d}}{d} E,$$

$$\Theta_{5,5} = \frac{e^{-\alpha d}}{d} M,$$

$$\Theta_{6,6} = \frac{\alpha}{\bar{w}^2},$$

$$\mathcal{A}_i = \begin{bmatrix} (A_i + B_i \Sigma K_i) N & A_i N & 0 & 0 & 0 & D_i N \end{bmatrix},$$

$$\mathcal{H}_i = \begin{bmatrix} \sigma_1 B_i H_n K_1 & 0_{m,n,1} & 0_{m,n} \\ \vdots & \sigma_m B_i H_m K_n & 0_{m,n} \end{bmatrix},$$

$$\mathcal{X} = \text{diag} \{ N, \ldots, N \}.$$


Then, the reachable set of system (11) can be bounded by the ellipsoid $\epsilon(P_i)$.

**Proof.** We consider the following Lyapunov–Krasovskii functional candidate for systems (11) as

$$V(x_i, r_i, t) = \sum_{m=1}^{5} V_m(x_i, r_i, t),$$

where

$$V_1(x_i, r_i, t) = x^T(t)P_r x(t),$$

$$V_2(x_i, r_i, t) = \int_{t-d}^{t} e^{\alpha(t-s)} x^T(s)Q_r x(s)ds + \int_{t-d(t)}^{t} e^{\alpha(t-s)} x^T(s)Sx(s)ds,$$

$$V_3(x_i, r_i, t) = \int_{t-d}^{t} e^{\alpha(t-s)} x^T(s)Rx(s)ds,$$

$$V_4(x_i, r_i, t) = \int_{t-d}^{t} e^{\alpha(t-s)} (d - t + s)x^T(s)Mx(s)ds,$$

$$V_5(x_i, r_i, t) = d \int_{-d}^{0} \int_{t+\theta}^{t+\Delta t} e^{\alpha(t-s)} x^T(s)N\dot{x}(s)ds d\theta.$$

Define the weak infinitesimal operator $E$ for the Lyapunov functional together with Markovian jump system (11) as

$$EV(x_i, r_i, t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} \left[ E[V(x_i, r_i, t + \Delta t | x_i, r_i = i)] - V(x_i, r_i, t) \right].$$

Furthermore, we have

$$EV_1(x_i, i, t) = 2x^T(t)P_r \dot{x}(t) + x^T(t) \sum_{j=1}^{N} \pi_{ij} P_j x(t) - \alpha V_1(x_i, i, t) + \alpha V_1(x_i, i, t),$$

$$EV_2(x_i, i, t) = x^T(t)Q_r x(t) - e^{-\alpha d} x^T(t - d)Q_r x(t - d) + \int_{t-d}^{t} e^{\alpha(t-s)} x^T(s) \sum_{j=1}^{N} \pi_{ij} Q_j x(s)ds$$

$$+ x^T(t)Sx(t) - (1 - \mu)e^{-\alpha d(t)} x^T(t - d(t))Sx(t - d(t)) - \alpha V_2(x_i, i, t),$$

$$EV_3(x_i, r_i, t) = x^T(t)Rx(t) - e^{-\alpha d} x^T(t - d)Rx(t - d) - \alpha V_3(x_i, i, t),$$

$$EV_4(x_i, i, t) = dx^T(t)Mx(t) - \int_{t-d}^{t} e^{\alpha(t-s)} x^T(s)Mx(s)ds - \alpha V_4(x_i, i, t),$$

$$EV_5(x_i, i, t) = d^2 x^T(t)N\dot{x}(t) - d \int_{t-d}^{t} e^{\alpha(t-s)} x^T(s)N\dot{x}(s)ds - \alpha V_5(x_i, i, t).$$
Considering the circumstance that the information of transition probabilities is not completely known, for any arbitrary matrices $W_i = W_i^T$ and $Z_j = Z_j^T$, the following zero equations hold due to $\sum_{j=1}^{N} \pi_{ij} = 0$:

$$-x^T(t) \sum_{j=1}^{N} \pi_{ij} W_i x(t) = 0, \quad (32)$$

$$- \int_{t-d}^{t} e^{\alpha(t-s)} x^T(s) \sum_{j=1}^{N} \pi_{ij} Z_j x(s) ds = 0. \quad (33)$$

Using Lemmas 1 and 3 to the integral terms in equations (30) and (31), we have

$$- \int_{t-d}^{t} e^{\alpha(t-s)} x^T(s) M x(s) ds \leq - e^{-\alpha d} \int_{t-d}^{t} x^T(s) M x(s) ds$$

$$= - e^{-\alpha d} \left[ \int_{t-d(t)}^{t} x^T(s) M x(s) ds + \int_{t-d(t)}^{t-d(t)} x^T(s) M x(s) ds \right]$$

$$= - e^{-\alpha d} \left[ \frac{d}{d(t)} \int_{t-d(t)}^{t} x(s) ds \right]^T M \left[ \int_{t-d(t)}^{t} x(s) ds \right]$$

$$- \frac{d}{d(t)} \int_{t-d(t)}^{t-d(t)} x(s) ds \right]^T M \left[ \int_{t-d(t)}^{t-d(t)} x(s) ds \right], \quad (34)$$

where the matrices $M$ and $E$ satisfy $\begin{bmatrix} M & E \\ * & M \end{bmatrix} \geq 0$. Similarly, we have

$$- d \int_{t-d}^{t} e^{\alpha(t-s)} x^T(s) N \dot{x}(s) ds \leq - e^{-\alpha d} \left[ \int_{t-d(t)}^{t} \dot{x}(s) ds \right]^T \begin{bmatrix} N & E_1 \\ * & N \end{bmatrix} \left[ \int_{t-d(t)}^{t} \dot{x}(s) ds \right], \quad (35)$$

$$\leq - e^{-\alpha d} \begin{bmatrix} x(t) - x(t-d(t)) \\ x(t-d(t)) - x(t-d) \end{bmatrix}^T \begin{bmatrix} N & E_1 \\ * & N \end{bmatrix} \begin{bmatrix} x(t) - x(t-d(t)) \\ x(t-d(t)) - x(t-d) \end{bmatrix}, \quad (36)$$
where the matrices $N$ and $E_i$ satisfy $\begin{bmatrix} N & E_i \\ * & N \end{bmatrix} \succeq 0$.
any \( t \geq t_0 \). Under the construction of the LKF in (17), we have \( x^T(t)P_x(t) \leq V(x(t),t) \leq 1 \), which means that the reachable set \( \mathcal{R}_x \) of the considered system (11) is bounded via the ellipsoid \( \varepsilon(P) \). Hence, this proof is finished.

Now, we are going to solve the delay-dependent extended dissipative-based control for Markovian jump time-delayed systems with stochastic actuator failures.

**Theorem 2.** For any given scalars \( d \geq 0, \mu, \mu_i, \sigma_j (j = 1, \ldots, m) \), and \( \omega \) and the constant matrices \( \Phi_1, \Phi_2, \Phi_3, \) and \( \Phi_0 \), if there exists appropriately dimensioned matrices \( X_i > 0, \tilde{Q}_i > 0, \tilde{Q}_i, \tilde{S}_i, \tilde{M}_i > 0 \), and \( V > 0 \), symmetric matrices \( \tilde{E}_i, \tilde{E}_i, \tilde{W}_i, \tilde{Z}_i \), and a scalar \( \alpha > 0 \), the following LMIs hold for \( i, j \in \mathbb{N} \):

\[
\begin{bmatrix}
\Theta_{6 \times 6} & \tilde{H}_i^T & \Lambda_{1i} & \Sigma^T \\
* & -d^T V & 0 & 0 \\
* & * & -\tilde{H} & 0 \\
* & * & * & -Y_{1i} \\
* & * & * & * & -I
\end{bmatrix} < 0, \quad i \in \mathbb{T}_k^i,
\]

\[
\begin{bmatrix}
\Theta_{6 \times 6} & \tilde{H}_i^T & \Lambda_{1i} & \Sigma^T \\
* & -d^T V & 0 & 0 \\
* & * & -\tilde{H} & 0 \\
* & * & * & -Y_{1i} \\
* & * & * & * & -I
\end{bmatrix} < 0, \quad j \in \mathbb{T}_m^j,
\]

\[
\sum_{j \in \mathbb{T}_i^j} \pi_{ij} e^{-ad} [\tilde{Q}_{ij} - \tilde{Z}_{ij}] \leq 0,
\]

\[
\begin{bmatrix}
-W_i & X_i \\
* & -X_i
\end{bmatrix} \leq 0, \quad j \in \mathbb{T}_m^j, j \neq i,
\]

\[
e^{-ad} [\tilde{Q}_{ij} - \tilde{Z}_{ij}] \leq 0, \quad j \in \mathbb{T}_m^j, j \neq i,
\]

\[
X_{ij} - \tilde{W}_i \geq 0, \quad j \in \mathbb{T}_m^j, j = i,
\]

\[
e^{-ad} [\tilde{Q}_{ij} - \tilde{Z}_{ij}] \geq 0, \quad j \in \mathbb{T}_m^j, j = i,
\]

\[
\begin{bmatrix}
\tilde{M}_i & \tilde{E}_i \\
* & \tilde{M}_i
\end{bmatrix} \geq 0,
\]

\[
\begin{bmatrix}
\tilde{N} & \tilde{E}_{ii} \\
* & \tilde{N}
\end{bmatrix} \geq 0,
\]

\[
\tilde{E}_i \geq 0,
\]

\[
\tilde{M}_i \geq 0,
\]

\[
\tilde{N} \geq 0,
\]

where

\[
\tilde{V}_{ij} = 2(A_i X_i + B_i \tilde{E}_i) - \sum_{j \in \mathbb{T}_i} \pi_{ij} \tilde{W}_i + \pi_{jj} \tilde{Q}_i + \tilde{S}_i + \alpha X_i + \tilde{R}_i + d \tilde{M}_i - e^{-ad} \tilde{N},
\]

\[
\tilde{V}_{ii} = A_i X_i + e^{-ad} (\tilde{N} - t \tilde{E}_i),
\]

\[
\tilde{V}_{ij} = e^{-ad} \tilde{E}_i,
\]

\[
\tilde{V}_{ij} = X_i C_i^T \Phi_2 + X_i D_i,
\]

\[
\tilde{V}_{ij} = e^{-ad} (-d \tilde{S}_i + \tilde{E}_i + \tilde{E}_i^T - 2 \tilde{N}),
\]

\[
\tilde{V}_{ij} = e^{-ad} (\tilde{N} - t \tilde{E}_i),
\]

\[
\tilde{V}_{ij} = e^{-ad} \left[ \tilde{R}_i + \tilde{Q}_i + \tilde{N} \right],
\]

\[
\tilde{V}_{ij} = e^{-ad} \tilde{E}_i,
\]

\[
\tilde{V}_{ij} = e^{-ad} \tilde{M}_i,
\]

\[
\tilde{V}_{ij} = \frac{C_i^T \Phi_2 - \alpha}{\tilde{M}_i},
\]

\[
\tilde{V}_{ij} = \left[ A_i + B_i \tilde{E}_i, A_i X_i, 0, 0, 0, D_i \right],
\]

\[
\tilde{V}_{ij} = \left[ \left[ \sigma_i B_i H_i, K_i \right], \right.
\]

\[
\tilde{V}_{ij} = \left[ \sigma_i B_i H_i, K_i \right], \quad \tilde{V}_{ij} = \left[ \sigma_i B_i H_i, K_i \right], \quad \tilde{V}_{ij} = \left[ \sigma_i B_i H_i, K_i \right],
\]

Then, the reachable set of the closed-loop system (1) is bounded by the prescribed ellipsoid in \( \varepsilon(X_i) \), and the desired state-feedback controller can be obtained as \( K_i = Y_i X_i^{-1} \).

**Proof.** Next, we design a dissipative-based stochastic fault-tolerant controller \( K_i \), such that the reachable set of system
(11) is bounded by a given ellipsoid $\varepsilon(P_i)$. This theorem is followed from Theorem 1 and the same line as in previous theorem; then, we have

$$\left[ EV(x_i,i,t) + aV(x_i,i,t) - \frac{\alpha}{\omega} \omega^T(t)\omega(t) + \pi(t) \right] < \varepsilon_1(t) \lambda(t)$$

where

$$\lambda(t) = \Theta_1 \Sigma^T < 0.$$  \hfill (49)

$$\Sigma = \begin{bmatrix} C_i^T \Phi_1 & 0 & 0 & 0 & C_i^T \Phi_1 \end{bmatrix}, \quad \Theta_{1,6} = C_i^T \Phi_2 + D_i,$$

$$\Theta_{6,6} = C_i^T \Phi_2 - \alpha/\omega^2,$$

and the rest of $\Theta_j$ are the same in Theorem 1. Defining $X_i = P_i^{-1}$ and applying the congruence transformation $\text{diag}(X_i, X_i, X_i, X_i, I, N, \mathcal{X}_i)$, where $\mathcal{X}_i = N_{t_1, \ldots, N_t}$ to (49) and setting $\tilde{Q}_i = X_iQX_i$, $\tilde{S}_i = X_iSX_i$, $\tilde{K}_i = \tilde{K}_iX_i^{-1}$, we obtain the LMI in Theorem 2. Then, under zero initial condition,

$$EV(x_i,i,t) + aV(x_i,i,t) - \frac{\alpha}{\omega} \omega^T(t)\omega(t) - \Xi(t) \leq 0.$$  \hfill (50)

Applying Dynkin’s formula, we have

$$\int_0^{T_f} \mathcal{Z}(s)ds \geq E\left[ (V(x_i,i,i)) + e^{\alpha(s-t)}E[V(x_0,i,i)] \right]$$

$$- \frac{\alpha}{\omega} \omega^T(t)\omega(t),$$ \hfill (51)

$$\geq x^T(t)P_i x(t) + \rho.$$ \hfill (51)

To prove extended dissipative, we consider two cases $\|\Phi_4\| = 0$ and $\|\Phi_4\| > 0$, respectively. First, if $\|\Phi_4\| = 0$, then (51) follows for any $T_f \geq 0$ that

$$\int_0^{T_f} \mathcal{Z}(s)ds \geq 0.$$ \hfill (52)

This satisfies the definition $\|\Phi_4\| = 0$. Furthermore, when $\|\Phi_4\| > 0$ as mentioned in Assumption 1, we have the matrices $\Phi_1 = 0, \Phi_2 = 0, \Phi_4 > 0$. For any $0 \leq t \leq t_f$, we have

$$E\left\{ \int_0^{T_f} \mathcal{Z}(t)dt \right\} \geq E\left\{ \int_0^{T_f} \mathcal{Z}(t)dt \right\} + \rho.$$ \hfill (52)

Then, there exist a scalar $0 < b < 1$ s.t. $E\left\{ \int_0^{T_f} \mathcal{Z}(t)dt \right\} \geq \{x^T(t)\tilde{\Theta}_i x(t)\} + \rho.$

Then, by (51), we have

$$x^T(t)\Phi_4 x(t) = b x^T(t) C_i^T \Phi_4 C_i x(t) \leq b x^T(t) P_i x(t).$$ \hfill (53)

It is mentioned that for any $0 \leq t \leq T_f,$

$$E\left\{ \int_0^{T_f} J(t)dt \right\} \geq z^T(t)\Phi_4 z(t) + \rho.$$ \hfill (54)

Thus, inequality (54) holds for all $T_f \geq 0$. This completes the proof.

\textbf{Remark 1.} It is noted that the condition in equations (39)–(46) are LMIs with respect to all the matrix variables. In order to obtain an ellipsoid with the shortest major principal axis for the reachable set of closed-loop system (11), we can maximise a positive scalar $\delta$ with respect to LMIs (39) and

$$X_i^{-1} \geq \delta I.$$ \hfill (55)

We use the following approximation of the above inequality:

$$\min \delta \quad \text{s.t.} \quad X_i \geq \delta I, \quad \text{subject to the LMIs (39)–(46)}.$$

\textbf{Remark 2.} It is noted that most of the existing studies based on Markovian jump systems subject to fully known transition probabilities. However, in practice, it is not an easy way to scale all transition probabilities because its cost is very expensive. Therefore, the considered problems based on Markovian jump time-delayed systems with partially known probabilities is more convenient than existing works [13, 24, 29] during the jump process.

\textbf{Remark 3.} It is noted that our considered control model (10) is indeed effective in improving the performances of dynamical time-delay systems. Moreover, compared with the existing feedback reliable control approaches [25–27], our stochastic fault-tolerant controller under actuator saturation achieves better performance when information of the random variable is available. Furthermore, existing fault-tolerant control approaches are only designed under the assumption of actuator fault matrix which is partially failure or fully failure. Nevertheless, in practice, the actuators may not be failures under the cases, namely, electromagnetic inferences, nonlinear amplification, and cipher deviation. Based on the above facts, the actuator fault matrix need to satisfy a convinced random circulation in the probability time bound values between zero and one. Hence, it is necessary and important to take such nondeterministic fluctuating term in our proposed method.

Now, consider the following time-delay system:

$$\begin{aligned}
\dot{x}(t) &= Ax(t) + A_2 x(t-d(t)) + D\omega(t), \\
x(t) &= \phi(t), \quad t \in [-d, 0].
\end{aligned}$$ \hfill (56)

Next, we provide a corollary for finding an ellipsoid to bound the reachable set of the time-delay system (56).

\textbf{Corollary 1.} For some scalars $d \geq 0, \mu, \alpha, \text{ and } \bar{\omega},$ if there exist appropriately dimensioned matrices $P > 0, Q > 0, R > 0, S > 0, M > 0,$ and $N > 0,$ any matrices $E$ and $E_1$ such that the following LMIs hold:
Proof. Choose the Lyapunov functional candidate as follows:

\[ V(t,x(t)) = \sum_{i=1}^{5} V_i(t,x(t)), \]

where

\[ V_i(t,x(t)) = x^T(t)Px(t), \]

\[ V_2(t,x(t)) = \int_{t-d}^{t} e^{a(t-s)} x^T(s)Qx(s)ds \]

\[ + \int_{t-d(t)}^{t} e^{a(t-s)} x^T(s)Sx(s)ds, \]

\[ V_3(t,x(t)) = \int_{t-d}^{t} e^{a(t-s)} (d - t + s)x^T(s)Mx(s)ds, \]

\[ V_4(t,x(t)) = d \int_{t-d}^{t} e^{a(t-s)} x^T(s)Nx(s)dsd\theta. \]

By following the similar steps as in Theorem 1 with small changes, the proof is omitted here. □

Remark 4. It is noted that the dissipative performance of this paper consists of some well-known control-based performances. For instance, by setting \( \Psi_1 = 0, \Psi_2 = 0, \Psi_3 = \gamma I, \) inequality (15) becomes the \( L_\infty - L_\infty \) performance. If we fix \( \Psi_1 = -I, \Psi_2 = 0, \Psi_3 = \gamma I, \) and \( \Psi_4 = 0, \) inequality (15) reduces to the \( H_\infty \) case. By choosing \( \Psi_1 = 0, \Psi_2 = I, \Psi_3 = \gamma I, \) and \( \Psi_4 = 0, \) inequality (15) becomes a passivity-based control. When we take \( \Psi_1 = -\gamma^{-1} I, \Psi_2 = (1 - \theta), \Psi_3 = \gamma \theta, \) and \( \Psi_4 = 0, \) inequality (15) corresponds to mixed \( H_\infty \) and passivity case. Furthermore, when we set \( \Psi_1 = 0, \Psi_2 = \emptyset, \Psi_3 = S, \) and \( \Psi_4 = R - M I, \) inequality (15) changes to the \( (\emptyset, S, R) \)-dissipative performance.

4. Numerical Simulation

In this section, numerical examples are provided to demonstrate the feasibility of the approaches proposed in this paper.

Example 1. Consider Markovian jump time-delayed system (11) with four modes and the following parameters:

\[ A_1 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}, \]

\[ A_{d1} = \begin{bmatrix} -1 & 0 \\ -1 & 0.9 \end{bmatrix}, \]

\[ B_1 = \begin{bmatrix} -1 & -1 \\ -1.5 & 0 \end{bmatrix}, \]

\[ D_1 = \begin{bmatrix} 1 \\ -0.3 \end{bmatrix}, \]

\[ A_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1.2 \end{bmatrix}, \]

\[ A_{d2} = \begin{bmatrix} -1.3 & -0.9 \\ 0 & -1.2 \end{bmatrix}, \]

\[ B_2 = \begin{bmatrix} -1.2 & -1.1 \\ 1.3 & 0.3 \end{bmatrix}, \]

\[ D_2 = \begin{bmatrix} 1 \\ -0.35 \end{bmatrix}, \]

\[ A_3 = \begin{bmatrix} 0 & 0 \\ 0 & 0.9 \end{bmatrix}, \]

\[ A_{d3} = \begin{bmatrix} -1.3 & -1.1 \\ 0 & -1.1 \end{bmatrix}, \]

\[ B_3 = \begin{bmatrix} -1.1 & -1.2 \\ 1.1 & 0.2 \end{bmatrix}, \]

\[ D_3 = \begin{bmatrix} 1 \\ -0.44 \end{bmatrix}, \]

\[ A_4 = \begin{bmatrix} 0 & 0 \\ 0 & 1.1 \end{bmatrix}, \]

\[ A_{d4} = \begin{bmatrix} -0.9 & -0.9 \\ 0 & -1.1 \end{bmatrix}, \]

\[ B_4 = \begin{bmatrix} -0.9 & -0.7 \\ 0.9 & 0.1 \end{bmatrix}, \]

\[ D_4 = \begin{bmatrix} 1 \\ -0.5 \end{bmatrix}. \]
Output matrices are taken as follows:
\[ C_{11} = C_{13} = [0.01 \ 0.15], \]
\[ C_{12} = C_{14} = [0.13 \ 0.12], \]
\[ C_{21} = C_{23} = 0.7, \]
\[ C_{22} = C_{24} = 0.5. \]  

We assume that the partially known transition rate matrix is given by
\[
\begin{bmatrix}
-1.5 & 0.2 & ? & ? \\
? & ? & 0.3 & 0.4 \\
0.6 & ? & -1.5 & ? \\
? & ? & 0.4 & ?
\end{bmatrix}
\]  

Here, we consider two cases:

**Case 1.** Let us take that the actuator is normal. Given \( \Xi = I, \)
\( \sigma_1 = 0.2, \) \( \mu = 0.5, \) \( d = 2.6, \) and \( \bar{\omega} = 1 \) and variances \( \sigma_1 = 0, \)
\( \sigma_2 = 0, \) \( \Phi_1 = 0.4I, \) \( \Phi_2 = 0.6I, \) \( \Phi_3 = 1.5I, \) and \( \Phi_4 = 0.3I. \) The
state responses of the open-loop system are given in Figure 1, and it is seen that the open-loop system is unstable. By solving the LMI conditions in Theorem 2 with disturbance input \( \omega(t) = 0.03 \cos(t) \) and initial condition \( x(0) = [-1, 1.5], \) we obtain a set of feasible solutions. The controller gain matrices are displaced as follows:
\[
K_1 = \begin{bmatrix}
-0.0601 & 2.7657 \\
2.7150 & -3.2046
\end{bmatrix},
\]
\[
K_2 = \begin{bmatrix}
-1.0415 & -3.2847 \\
3.1851 & 3.5214
\end{bmatrix},
\]
\[
K_3 = \begin{bmatrix}
-0.7894 & -2.8499 \\
2.4435 & 2.5206
\end{bmatrix},
\]
\[
K_4 = \begin{bmatrix}
-0.0332 & 2.5530 \\
2.5321 & -2.9344
\end{bmatrix}.
\]

Based on the controller gain matrices, the state trajectories and bounding reachable set of system (11) are shown in Figures 2 and 3, respectively. Moreover, Figure 2 represents the reachable set of system (11) bounded by the ellipsoid \( \varepsilon(X)^{-1}. \) Also, it is observed from Figure 3 that the state feedback controller stabilizes system (11) in the presence of partially known transition probabilities.

**Case 2.** Consider the stochastic actuators failures with \( \Xi = 0.7I, \) \( \mu_1 = 0.2, \) and \( \mu_2 = 0.3 \) and \( \sigma_1 = 0.5 \) and \( \sigma_2 = 0.6. \) Choose the values \( \alpha = 0.2, \) \( \mu = 0.5, \) \( d = 2.70, \) \( \bar{\omega} = 1, \) \( \Phi_1 = 0.4I, \) \( \Phi_2 = 0.6I, \) \( \Phi_3 = 1.5I, \) \( \Phi_4 = 0.3I \) together with the transition probability matrix given in (47), and solving the LMIs in Theorem 2 with aid of the MATLAB LMI tool box,
we can get feasible solutions, which are not given here. Moreover, the corresponding gain matrices are calculated as follows:

\[
K_1 = \begin{bmatrix} 0.2251 & 3.1203 \\ 0.3003 & -0.0232 \end{bmatrix}, \\
K_2 = \begin{bmatrix} 0.0825 & -0.2493 \\ 0.1575 & -0.0852 \end{bmatrix}, \\
K_3 = \begin{bmatrix} 0.1208 & -0.8841 \\ 0.2189 & -0.1490 \end{bmatrix}, \\
K_4 = \begin{bmatrix} 0.1480 & 0.2450 \\ 0.2295 & -0.0019 \end{bmatrix},
\]

The obtained ellipsoid \( \varepsilon(X_i^{-1}) \) and the state trajectory of system (11) with the proposed controller are shown in Figures 4 and 5. It is seen from Figure 4 that the reachable set of system (11) is contained in the ellipsoid \( \varepsilon(X_i^{-1}) \). Also, it is observed from Figure 5 that when actuator failures occur, system (11) with the proposed reliable controller operates well and maintains the system stability. Next, the reachable set of system (11) is contained in \( \varepsilon(X_i^{-1}) \) when \( \alpha = 0.25 \), which is shown in Figure 6. Figure 7 shows the mode transition rates of the closed-loop system (11). Furthermore, in Table 1, we estimate the values of \( \delta_{\min} \) for different values of \( d \). From the simulation analysis, it is easy to understand that the considered Markovian jump system (11) is bounded and extended dissipative even in the occurrence of partially known transition probabilities, time delay, stochastic faults, uncertain parameters, and external disturbances.

**Example 2.** In this numerical result, we consider an electrical circuit as given in Figure 6 [29] where \( i_L(t) \) and \( u_c(t) \) represent the currents passing through the inductances and the voltage across the capacitor, respectively. Then, by using the Kirchhoff laws, we obtain for \( r(t) = 1, 2, \ldots \)
Now, we set $x_1(t) = u_c(t)$ and $x_2(t) = i_L(t)$, and assume that there exists the noise signal $w(t) \in \mathbb{R}^n$, which is assumed to be an arbitrary signal in $L_2[0, \infty)$, then the electrical circuit of Figure 6 [29] can be arranged as the Markovian jump system with the following parameters:

$$
\begin{align*}
\frac{di_L(t)}{dt} &= \frac{u_L(t) - u_c(t) - i_L(t)}{L(r(t))}, \\
\frac{du_c(t)}{dt} &= \frac{i_L(t)}{C(r(t))}.
\end{align*}
\tag{66}
$$

Now, we set $x_1(t) = u_c(t)$ and $x_2(t) = i_L(t)$, and assume that there exists the noise signal $w(t) \in \mathbb{R}^n$, which is assumed to be an arbitrary signal in $L_2[0, \infty)$, then the electrical circuit of Figure 6 [29] can be arranged as the Markovian jump system with the following parameters:

$$
\begin{align*}
A_1 &= \begin{bmatrix} 0 & \frac{1}{C_1} \\ \frac{1}{L_1} & \frac{R}{L_1} \end{bmatrix}, \\
A_2 &= \begin{bmatrix} 0 & \frac{1}{C_2} \\ \frac{1}{L_1} & -\frac{R}{L_1} \end{bmatrix}, \\
B_{11} &= \begin{bmatrix} 0 \\ \frac{1}{L_1} \end{bmatrix}, \\
B_{12} &= \begin{bmatrix} 0 \\ \frac{1}{L_2} \end{bmatrix}
\end{align*}
\tag{67}
$$

where $C_1 = 0.5F, C_2 = 0.8F, R = 0.01\Omega, L_1 = 4H, L_2 = 8H$, and the remaining matrices of system (11) are taken as zero. Taken, the other positive values are $\Xi = 0.6I$, $\mu_1 = 0.3$, $\mu_2 = 0.2$ and $\sigma_1 = 0.37$ and $\sigma_2 = 0.57$, with the transition probability matrix given in (47), and solving the LMIs in Theorem 2 with help of MATLAB LMI tool box, we obtain feasible solutions, and controller gain matrices are displayed as follows:

$$
\begin{align*}
K_1 &= \begin{bmatrix} -0.0867 & -1.4364 \end{bmatrix}, \\
K_2 &= \begin{bmatrix} -0.4654 & -2.9528 \end{bmatrix}.
\end{align*}
\tag{68}
$$

We consider the initial condition

$$
\phi(t) = \begin{bmatrix} 0.5e^{t} & e^{0.3t} \end{bmatrix}^T, t \in [-0.9, 0].
$$

Based on the gain

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{simulation_results}
\caption{Simulation results of the closed-loop system (11).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{mode_transition_rates}
\caption{Mode transition rates $r(t)$.}
\end{figure}
matrices, the state responses and control curve of the closed-loop system (11) are presented in Figure 8. Furthermore, Figure 9 represents the mode transition rates $r(t)$ of the closed-loop system (11). Under the simulation result, it is concluded that proposed system (11) is stochastically stable and extended dissipative even in the presence of stochastic fault, uncertain parameters, and gain fluctuations. Hence, our proposed controller is an active one to stabilize Markovian jump system (11) with respect to stochastic fault.

5. Conclusion

In this work, we have investigated the reachable set bounding and extended dissipative controller synthesis of time-delayed Markovian jump systems with partially known transition probabilities and stochastic actuator failures and bounded disturbances. A new practical actuator fault model is designed to achieve a less conservative result, not only when the system is operating properly but also in the presence of certain actuator failures. Based on the LKF, reciprocal convex approach, Jensen’s integral inequality, and novel reachable set lemma, a new set of delay-dependent LMI conditions is constructed in the form of LMIs for estimating an ellipsoid to bound the reachable sets of Markovian jump time-delayed systems with disturbances. Then, this result is extended to the control design of considered systems with extended dissipative performance indices. Two numerical simulation examples have been provided to demonstrate the effectiveness of the proposed methods. Then, the problem of the event-triggered control for a class of T-S fuzzy semi-Markovian jump systems with stochastic cyberattacks randomly gain variations, and bounded disturbances are an untreated work, which will be the topic of our future work.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

All authors contributed equally to the manuscript. All authors read and approved the manuscript.

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