International Journal of Control, Automation and Systems 19(8) (2021) 2687-2696
http://dx.doi.org/10.1007/s12555-020-0652-x
ISSN:1598-6446 eISSN:2005-4092
http://www.springer.com/12555

Finite-time Event-triggered Extended Dissipative Control for a Class of Switched Linear Systems

Hui Gao*, Kaibo Shi, Hongbin Zhang, and Jianwei Xia

Abstract: This paper investigates the problem of event-triggered finite-time extended dissipative control for a class of switched linear systems. We propose a novel event-triggered method that allows frequent system switching over an event-triggered interval, which is different from the previous work that only one switching happened over the event-triggered interval. By average dwell time and a novel controller-mode-dependent Lyapunov function method, we give sufficient conditions for finite-time extended dissipative analysis of the closed-loop switched linear system. LMIs are used for the design of the controller. Finally, numerical examples are given to illustrate the effectiveness of the proposed method.

Keywords: Event-trigger, extended dissipative control, finite-time, frequent asynchronism.

1. INTRODUCTION

Switched system belongs to a special class of hybrid systems, which can be modeled by a class of discrete or continuous-time subsystems and a logical rule that orchestrates the switching among the subsystems. It has attracted remarkable attention for its practical applications in traffic control, electrical systems and so on [1–5]. For example, switched model predictive control of switched linear systems:Feasibility, stability and robustness is investigated in [3], improved results on stability of continuous-time switched positive linear systems is researched in [4], respectively.

In many real world situations, especially in missile systems, chemical reaction process and robot control systems. The system behavior over a short time interval is very important, which required that the system state should not exceed a bounded domain over finite time. Compared with Lyapunov asymptotic stability, finite-time stability is more realistic and theoretical. Thus we are interested analysing finite-time stability of the switched systems and many results have been proposed for the related issues [6–9]. Specially, reliable finite-time filtering for impulsive switched linear systems with sensor failures is researched in [8], asynchronously switched control of a class of slowly switched linear systems is investigated in [9] and so on.

The problem of sampled-data control has been excessively studied over the past decades, the periodic sampling or time-triggered sampling mechanism is the traditional method. However, this method may lead to unnecessary data transmission, which is undesired in practical engineering, especially in some networked control systems with limited communication bandwidth. On the other hand, event-triggered control is a hot topic in recent years, which can reduce the transmission resource efficiently compared with the periodic sampling. The event-triggered control method has been developed rapidly, especially for switched systems, for example, adaptive event-triggered control, observer based event-triggered control and so on. There are so many results occured [10–12]. However, the switching feather mixed event-triggered sampling makes it difficult to the analysis and synthesis of the switched system. For the difficulty dealing with asynchronism between subsystem and event-triggered controller, many works assume that at most one switching happens during an inter-event interval, which is unrealistic and not practical. Inspired by the work [5], which firstly searched the system switch more than once during the event-triggered period. We extended the method of [5] for switched linear systems with frequent switching over an inter-event interval, which motivates our current study.

The concept of extended dissipative was proposed by Zhang in [13], which unifies H_∞ performance, L_2-L_∞ performance, Passivity performance and (Q, S, R)-dissipativity performance together. It provids an efficient

Manuscript received September 8, 2020; revised October 27, 2020; accepted November 9, 2020. Recommended by Associate Editor Guangdeng Zong under the direction of Editor Hamid Reza Karimi. The work was supported by the National Natural Science Foundation of China (Grants no. 61971100).

Hui Gao and Hongbin Zhang are with the School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan 611731, P. R. China (e-mails: gaohui194011@sina.com, zhanghb@uestc.edu.cn). Kaibo Shi is with the School of Information Science and Engineering, Chengdu University, Chengdu 610106, P. R. China (e-mail: skbs111@163.com). Jianwei Xia is with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, P. R. China (e-mail: njustxjw@126.com).
* Corresponding author.

Springer
©ICROS, KIEE and Springer 2021

method for system performance analysis and has attracted remarkable attention [13–15]. So we are interested analysing the extended dissipative performance for switched linear systems.

The contributions of this paper are listed as follows: 1) A novel event-triggered method with frequent switching over an inter-event interval is proposed; 2) Finite-time extended dissipative performance is analysed for switched linear systems; 3) The novel controller-mode dependent Lyapunov functional is used for system analysis; 4) Matrix transformation technique is used for the controller design.

This paper is organized as follows: In Section 2, system descriptions and preliminaries are formulated. In Section 3, sufficient conditions of event-triggered finite-time extended dissipative control for switched linear systems are established. The design method of the state feedback controllers is proposed. In Section 4, numerical examples are presented. In Section 5, conclusion is given.

Notation: M^T represents the transpose of the matrix M; $X>0$ denotes a positive-definite matrix. $\lambda_{min}(P)$, $\lambda_{max}(P)$ denote the minimum and maximum eigenvalue of matrix P respectively.

2. SYSTEM DESCRIPTIONS AND PRELIMINARIES

Consider the following switched linear system:

$$\begin{aligned}&\dot{x}(t)=A_{\sigma(t)}x(t)+B_{\sigma(t)}u(t)+C_{\sigma(t)}w(t),\\&y(t)=D_{\sigma(t)}x(t),\\&x(t_0+\theta)=\varphi(\theta),\forall\theta\in[-\tau,0],\end{aligned}\qquad(1)$$

where $x(t)\in R^n$ is the state vector, $u(t)$ is the control input, $w(t)$ is the exogenous disturbance which belongs to $L_2[0,\infty)$, $L_2[0,\infty)$ denote something is bounded, $y(t)\in R^n$ is the output of the system, $\varphi(\theta)$ is the initial condition of the system on $[-\tau,0]$. The switching signal $\sigma(t):[0,\infty)\mapsto M=\{1,2...l\}$ is a piecewise continuous function and for each $\sigma(t)=i$, A_i,B_i,C_i,D_i are known constant matrices. Let $t_q,q\in N$, be the switching instant, where $N\in N^+$ stands for the positive integer.

Given the event-triggered scheme:

$t_{k+1}=min\{t_k+T<t<t_k+G\,|\,[x(t)-x(t_k)]^T\Phi_{\sigma(t_k)}[x(t)-x(t_k)]\geq\varepsilon x(t_k)^T\Phi_{\sigma(t_k)}x(t_k)\}$, t_k denotes the sampling instants for any integer $k\geq0$. $\Phi_{\sigma(t_k)}$ is positive definite matrices to be determined, $\varepsilon>0$ and $0<T<\tau_a$ are given event-triggered parameters. Note that the parameter T in the event-triggered mechanism limits the lower bound of inter-event intervals and meanwhile avoids the Zeno behavior.The parameter G in the event-triggered mechanism limits the upper bound of inter-event intervals and meanwhile restricts the total asynchronous time, which not only facilitates the analysis and synthesis problems but also avoids the controller not updated for too long a time.

The state feedback control law is given as $u(t)=K_{\sigma(t_k)}x(t_k),t\in[t_k,t_{k+1})$. Denote $e(t)=x(t)-x(t_k)$, then $u(t)=K_{\sigma(t_k)}(x(t)-e(t)),t\in[t_k,t_{k+1})$.

Then the closed-loop system can be obtained.

$$\begin{aligned}&\dot{x}(t)=\overline{A}_{\sigma(t),\sigma(t_k)}x(t)-\overline{B}_{\sigma(t),\sigma(t_k)}e(t)+C_{\sigma(t)}w(t),\\&y(t)=D_{\sigma(t)}x(t),\\&x(t_0+\theta)=\varphi(\theta),\forall\theta\in[-\tau,0],t\in[t_q,t_{q+1}).\end{aligned}\qquad(2)$$

where

$$\begin{aligned}&\overline{A}_{\sigma(t),\sigma(t_k)}=(A_{\sigma(t)}+B_{\sigma(t)}K_{\sigma(t_k)}),\\&\overline{B}_{\sigma(t),\sigma(t_k)}=B_{\sigma(t)}K_{\sigma(t_k)}.\end{aligned}$$

Assume $\sigma(t_k)=i,\sigma(t_q)=j$, with $t_k<t_q$ and $\sigma(t)=j$ for all $t\in[t_q,t_{q+1})$.

We discuss the following two cases:

Case 1: If no event trigger happened in $[t_q,t_{q+1})$, i.e., $t_k<t_q<t_{q+1}\leq t_{k+1}$, then the system is the form:

$$\begin{aligned}&\dot{x}(t)=\overline{A}_{j,i}x(t)-\overline{B}_{j,i}e(t)+C_jw(t),\\&y(t)=D_jx(t),\\&x(t_0+\theta)=\varphi(\theta),\forall\theta\in[-\tau,0],t\in[t_q,t_{q+1}),\end{aligned}$$

where $e(t)=x(t)-x(t_k),t\in[t_q,t_{q+1})$.

Case 2: If there are $m(\in N+)$ triggered instants in $[t_q,t_{q+1})$, i.e., $t_k<t_q<t_{k+1}<\cdots<t_{k+m}\leq t_{q+1}<t_{k+m+1}$, then the system is the form

$$\begin{aligned}&\dot{x}(t)=\begin{cases}\overline{A}_{j,i}x(t)-\overline{B}_{j,i}e(t)+C_jw(t),\ t\in[t_q,t_{k+1}),\\\overline{A}_{j,j}x(t)-\overline{B}_{j,j}e(t)+C_jw(t),\ t\in[t_{k+1},t_{k+2}),\\\qquad\vdots\\\overline{A}_{j,j}x(t)-\overline{B}_{j,j}e(t)+C_jw(t),\ t\in[t_{k+m},t_{q+1}),\end{cases}\\&y(t)=D_jx(t),\\&x(t_0+\theta)=\varphi(\theta),\ \forall\theta\in[-\tau,0],\ t\in[t_q,t_{q+1}),\end{aligned}$$

where

$$e(t)=\begin{cases}x(t)-x(t_k),t\in[t_q,t_{k+1}),\\x(t)-x(t_{k+1}),t\in[t_{k+1},t_{k+2}),\\\qquad\vdots\\x(t)-x(t_{k+m}),t\in[t_{k+m},t_{q+1}).\end{cases}$$

We use $T_\uparrow[t_q,t_{q+1})$ and $T_\downarrow[t_q,t_{q+1})$ to denote the asynchronous and synchronous interval of $[t_q,t_{q+1})$, respectively, the system can be rewritten as

$$\begin{aligned}&\dot{x}(t)=\begin{cases}\overline{A}_{j,i}x(t)-\overline{B}_{j,i}e(t)+C_jw(t),\ \ t\in T_\uparrow[t_q,t_{q+1}).\\\overline{A}_{j,j}x(t)-\overline{B}_{j,j}e(t)+C_jw(t),\ \ t\in T_\downarrow[t_q,t_{q+1})\end{cases}\\&y(t)=D_jx(t),\\&x(t_0+\theta)=\varphi(\theta),\ \forall\theta\in[-\tau,0],\ \ t\in[t_q,t_{q+1}).\end{aligned}$$

Proposition 1 [1]**:** The external disturbance satisfies

$$\int_0^t w^T(s)w(s)ds \le d,\ \ d \ge 0.$$

Proposition 2 [13]**:** Matrices ψ_1, ψ_2, ψ_3, ψ_4 satisfy the following conditions:

1) $\psi_1 = \psi_1^T \le 0,\ \ \psi_3 = \psi_3^T > 0,\ \ \psi_4 = \psi_4^T \ge 0;$
2) $(\|\psi_1\| + \|\psi_2\|)\psi_4 = 0.$

Definition 1 [13]**:** Given matrices ψ_1, ψ_2, ψ_3 and ψ_4 satisfying Proposition 2, and for any $T_f \ge 0$ and all $w(t) \in L_2[0,\infty)$, system (2) is said to be extended dissipative if:

$$\int_0^{T_f} J(t)dt - \sup_{0\le t\le T_f} y^T(t)\psi_4 y(t) \ge 0, \tag{3}$$

where

$$J(t) = y^T(t)\psi_1 y(t) + 2y^T(t)\psi_2 w(t) + w^T(t)\psi_3 w(t). \tag{4}$$

Remark 1: By setting the weighting matrices, we have
1) $L_2 - L_\infty$ performance: $\psi_1 = 0$, $\psi_2 = 0$, $\psi_3 = \gamma^2 I$, $\psi_4 = I$;
2) H_∞ performance: $\psi_1 = -I$, $\psi_2 = 0$, $\psi_3 = \gamma^2 I$, $\psi_4 = 0$;
3) Passivity performance: $\psi_1 = 0$, $\psi_2 = I$, $\psi_3 = \gamma I$, $\psi_4 = 0$;
4) (Q,S,R)-dissipativity performance: $\psi_1 = Q$, $\psi_2 = S$, $\psi_3 = R - \beta I$, $\psi_4 = 0$.

Definition 2 [1]**:** Given positive constants c_1, c_2, T_f with $c_1 < c_2$, a positive definite matrix R and a switching signal $\sigma(t)$, $\forall t \in [0,T_f]$, switched system (2) is said to be finite-time bounded with respect to (c_1,c_2,R,T_f,σ), if $\forall t \in [0,T_f]$,

$$\begin{aligned}&\sup_{-\tau\le\theta\le 0}\{x^T(\theta)Rx(\theta),\ \dot{x}^T(\theta)R\dot{x}(\theta)\} \le c_1\\ &\Rightarrow x^T(t)Rx(t) \le c_2.\end{aligned} \tag{5}$$

Definition 3 [1]**:** For any $T_2 > T_1 \ge 0$, let $N_\sigma(T_1,T_2)$ denotes the switching number of $\sigma(t)$ over (T_1,T_2). If

$$N_\sigma(T_1,T_2) \le N_0 + \frac{T_2 - T_1}{\tau_a} \tag{6}$$

holds for $\tau_a > 0$ and an integer $N_0 \ge 0$, then τ_a is called an average dwell-time and N_0 is the chatter bound.

3. MAIN RESULTS

3.1. Finite-time boundedness and extended dissipative performance analysis

Theorem 1: If there exist positive scalars b, α, β and $\mu \ge 1$, positive definite matrices P_i, Q_i, Φ_i, such that the following matrix inequalities hold for all $i, j \in N$.

$$P_i \le \mu P_j,\ \forall i \ne j, \tag{7}$$

$$\frac{1}{b}P_i - D_i^T\psi_4 D_i > 0, \tag{8}$$

$$\begin{bmatrix} -\beta P_i + P_i\overline{A}_{ji} + \overline{A}_{ji}^T P_i & -P_i\overline{B}_{ji} & P_iC_j & \Phi_i \\ * & -\Phi_i & 0 & -\Phi_i \\ * & * & -Q_i & 0 \\ * & * & * & -\Phi_i \end{bmatrix} < 0, \tag{9}$$

$$\begin{bmatrix} \alpha P_j + P_j\overline{A}_{jj} + \overline{A}_{jj}^T P_j & -P_j\overline{B}_{jj} & P_jC_j & \Phi_j \\ * & -\Phi_j & 0 & -\Phi_j \\ * & * & -Q_j & 0 \\ * & * & * & -\Phi_j \end{bmatrix} < 0, \tag{10}$$

$$\begin{bmatrix} \Theta_{11} & -P_i\overline{B}_{ji} & P_iC_j - D_j^T\psi_2 & \Phi_i \\ * & -\Phi_i & 0 & -\Phi_i \\ * & * & -\psi_3 & 0 \\ * & * & * & -\Phi_i \end{bmatrix} < 0, \tag{11}$$

$$\Theta_{11} = -\beta P_i + P_i\overline{A}_{ji} + \overline{A}_{ji}^T P_i - D_j^T\psi_1 D_j,$$

$$\begin{bmatrix} \Xi_{11} & -P_j\overline{B}_{jj} & P_jC_j - D_j^T\psi_2 & \Phi_j \\ * & -\Phi_j & 0 & -\Phi_j \\ * & * & -\psi_3 & 0 \\ * & * & * & -\Phi_j \end{bmatrix} < 0, \tag{12}$$

$$\Xi_{11} = \alpha P_j + P_j\overline{A}_{jj} + \overline{A}_{jj}^T P_j - D_j^T\psi_1 D_j$$

hold, the average dwell-time satisfies

$$\tau_a \ge \frac{ln\mu + (\alpha+\beta)T}{\alpha}, \tag{13}$$

and

$$(\mu e^{(\alpha+\beta)T})^{N_0} e^{(\frac{ln\mu+(\alpha+\beta)T}{\tau_a} - \alpha)t}(\lambda_2 c_1 + \lambda_3 d) < \lambda_1 c_2, \tag{14}$$

$$(\mu e^{(\alpha+\beta)T})^{N_0} e^{(\frac{ln\mu+(\alpha+\beta)T}{\tau_a} - \alpha)t} < b, \tag{15}$$

we define

$$\begin{aligned}&\lambda_{min}(R^{-\frac{1}{2}}P_iR^{-\frac{1}{2}}) = \lambda_1, \lambda_{max}(R^{-\frac{1}{2}}P_iR^{-\frac{1}{2}}) = \lambda_2,\\ &\lambda_{max}(R^{-\frac{1}{2}}Q_iR^{-\frac{1}{2}}) = \lambda_3.\end{aligned} \tag{16}$$

Then the switched system (2) is finite-time boundedness with extended dissipative performance.

Proof: Choose the following Lyapunov functional as

$$V(t) = x^T(t)P_{\sigma(t_k)}x(t). \tag{17}$$

Case 1: If no triggered instant happened in $[t_q, t_{q+1})$, the closed-loop system is the same as the above Case 1 with $V(t) = x^T(t)P_ix(t)$. Then we have

$$\begin{aligned}&\dot{V}(t) - \beta V(t) - w^T(t)Q_iw(t)\\ &= 2x^T(t)P_i\dot{x}(t) - \beta x^T(t)P_ix(t) - w^T(t)Q_iw(t)\\ &\le 2x^T(t)P_i(\overline{A}_{ji}x(t) - \overline{B}_{ji}e(t) + C_jw(t))\\ &\quad - \beta x^T(t)P_ix(t) - w^T(t)Q_iw(t)\\ &\quad + [x(t) - e(t)]^T\Phi_i[x(t) - e(t)] - e(t)^T\Phi_ie(t)\end{aligned}$$

$$\leq X^T(t)\Omega_{ji}X(t), \tag{18}$$

where

$$X(t)=\begin{bmatrix} x^T(t) & e^T(t) & w^T(t) \end{bmatrix}^T,$$

and

$$\begin{aligned}\Omega_{ji}=&\begin{bmatrix} -\beta P_i+P_i\overline{A}_{ji}+\overline{A}_{ji}^TP_i & -P_i\overline{B}_{ji} & P_iC_j \\ * & -\Phi_i & 0 \\ * & * & -Q_i \end{bmatrix}\\ &+E^T\Phi_iE,\\ E=&\begin{bmatrix} I & -I \end{bmatrix}.\end{aligned}$$

From (9) , we have

$$\dot{V}(t)\leq \beta V(t)+w^T(t)Q_iw(t), t\in[t_q,t_{q+1}). \tag{19}$$

It can be concluded that

$$\begin{aligned}V(t_{q+1})=&V(t_{q+1}^{-1})\leq e^{\beta(t_{q+1}-t_q)}V(t_q)\\ &+e^{\beta(t_{q+1}-t_q)}\int_{t_q}^{t_{q+1}}w^T(s)Q_iw(s)ds,\\ &t\in[t_q,t_{q+1}).\end{aligned} \tag{20}$$

Case 2: When there are $m(\in N_+)$ triggered instants in $[t_q, t_{q+1})$, the closed-loop system is the same as the above Case 2 with

$$V(t)=\begin{cases} x^T(t)P_ix(t), & t\in[t_q,t_{k+1});\\ x^T(t)P_jx(t), & t\in[t_{k+1},t_{q+1}),\end{cases}$$

similar to Case 1 and considering (7), we have

$$\begin{aligned}V(t_{k+1})\leq&\mu V(t_{k+1}^{-1})\leq \mu e^{\beta(t_{k+1}-t_q)}V(t_q)\\ &+\mu e^{\beta(t_{k+1}-t_q)}\int_{t_q}^{t_{k+1}}w^T(s)Q_iw(s)ds,\\ &t\in[t_q,t_{k+1}).\end{aligned} \tag{21}$$

For $t\in[t_{k+1},t_{q+1})$, it holds that

$$\begin{aligned}&\dot{V}(t)+\alpha V(t)-w^T(t)Q_jw(t)\\ &=2x^T(t)P_j\dot{x}(t)+\alpha x^T(t)P_jx(t)-w^T(t)Q_jw(t)\\ &\leq 2x^T(t)P_j(\overline{A}_{jj}x(t)-\overline{B}_{jj}e(t)+C_jw(t))\\ &\quad+\alpha x^T(t)P_jx(t)-w^T(t)Q_jw(t)\\ &\quad+[x(t)-e(t)]^T\Phi_j[x(t)-e(t)]-e(t)^T\Phi_je(t)\\ &\leq X^T(t)\Omega_{jj}X(t),\end{aligned} \tag{22}$$

which implies

$$\dot{V}(t)\leq -\alpha V(t)+w^T(t)Q_jw(t).$$

From (10), we have

$$\begin{aligned}V(t_{q+1})=&V(t_{q+1}^{-1})\\ \leq&e^{-\alpha(t_{q+1}-t_{k+1})}V(t_{k+1})\\ &+e^{-\alpha(t_{q+1}-t_{k+1})}\int_{t_{k+1}}^{t_{q+1}}w^T(s)Q_jw(s)ds\\ \leq&\mu e^{-\alpha(t_{q+1}-t_{k+1})}(V(t_{k+1}^{-1})\\ &+\int_{t_{k+1}}^{t_{q+1}}w^T(s)Q_jw(s)ds)\\ \leq&\mu e^{-\alpha(t_{q+1}-t_{k+1})+\beta(t_{k+1}-t_q)}(V(t_q)\\ &+\int_{t_q}^{t_{q+1}}w^T(s)Q_jw(s)ds).\end{aligned} \tag{23}$$

Therefore, it can be concluded from (20) and (23) that

$$\begin{aligned}V(t_{q+1})\leq&\mu e^{-\alpha T_{\downarrow}[t_q,t_{q+1})}e^{\beta T_{\uparrow}[t_q,t_{q+1})}(V(t_q)\\ &+\int_{t_q}^{t_{q+1}}w^T(s)Q_iw(s)ds).\end{aligned} \tag{24}$$

The controller switching $\tilde{N}_\sigma(0,t)$ is smaller than system switching $N_\sigma(0,t)$. Then for any $t>0$,

$$\begin{aligned}V(t)\leq&\mu^{\tilde{N}_\sigma(0,t)}e^{-\alpha T_{\downarrow}[0,t)+\beta T_{\uparrow}[0,t)}\\ &\times\left(V(0)+\int_0^t w^T(s)Q_iw(s)ds\right)\\ \leq&\mu^{N_\sigma(0,t)}e^{-\alpha t}e^{(\alpha+\beta)TN_\sigma(0,t)}\\ &\times\left(V(0)+\int_0^t w^T(s)Q_iw(s)ds\right)\\ \leq&(\mu e^{(\alpha+\beta)T})^{N_0}e^{(\frac{ln\mu+(\alpha+\beta)T}{\tau_a}-\alpha)t}\\ &\times\left(V(0)+\int_0^t w^T(s)Q_iw(s)ds\right).\end{aligned} \tag{25}$$

On the other hand,

$$\begin{aligned}V(0)=&x^T(0)P_ix(0)=x^T(0)R^{\frac{1}{2}}(R^{-\frac{1}{2}}P_iR^{-\frac{1}{2}})R^{\frac{1}{2}}x(0)\\ \leq&\lambda_2c_1.\end{aligned} \tag{26}$$

We have

$$\begin{aligned}V(t)=&x^T(t)P_ix(t)=x^T(t)R^{\frac{1}{2}}(R^{-\frac{1}{2}}P_iR^{-\frac{1}{2}})R^{\frac{1}{2}}x(t)\\ \geq&\lambda_1x^T(t)Rx(t).\end{aligned} \tag{27}$$

From (25)-(27) we have that

$$x^T(t)Rx(t)<\frac{(\mu e^{(\alpha+\beta)T})^{N_0}e^{(\frac{\ln\mu+(\alpha+\beta)T}{\tau_a}-\alpha)t}(\lambda_2c_1+\lambda_3d)}{\lambda_1}.$$

Using (14), one obtains

$$x^T(t)Rx(t)<c_2.$$

Similar to the above proof, we have

$$\dot{V}(t)+\lambda V(t)-J(t)\leq X^T(t)\Phi_{\sigma(t)\sigma(t_k)}X(t),$$

where

$$\lambda = \begin{cases} \alpha, & t \in T_s[t_q, t_{q+1}); \\ -\beta, & t \in T_{as}[t_q, t_{q+1}), \end{cases}$$
$$X(t) = \begin{bmatrix} x^T(t) & e^T(t) & w^T(t) \end{bmatrix}^T,$$

by virtue of (11) and (12) we have that

$$\dot{V}(t) + \lambda V(t) - J(t) < 0.$$

Similar to above proof, we have

$$\begin{aligned} V(t) \leq &(\mu e^{(\alpha+\beta)T})^{N_0} e^{(\frac{ln\mu+(\alpha+\beta)T}{\tau_a} - \alpha)t} \\ &\times \left(V(0) + \int_0^t J(s)ds \right), \end{aligned} \tag{28}$$

under zero initial condition $V(0) = 0$, we have

$$V(t) \leq (\mu e^{(\alpha+\beta)T})^{N_0} e^{(\frac{ln\mu+(\alpha+\beta)T}{\tau_a} - \alpha)t} \int_0^t J(s)ds, \tag{29}$$

and it is equivalent to

$$\frac{V(t)}{(\mu e^{(\alpha+\beta)T})^{N_0} e^{(\frac{ln\mu+(\alpha+\beta)T}{\tau_a} - \alpha)t}} < \int_0^t J(s)ds,$$

by (15), we have

$$\frac{V(t)}{b} < \int_0^t J(s)ds,$$

so we have

$$\int_0^t J(s)ds > \frac{V(t)}{b} > \frac{1}{b} x^T(t) P_i x(t) > 0,$$

considering inequality

$$\int_0^{T_f} J(t)dt - \sup_{0 \leq t \leq T_f} y^T(t) \psi_4 y(t) \geq 0,$$

when $\psi_4 = 0$, one obtains

$$\int_0^{T_f} J(t)dt \geq 0,$$

when $\psi_4 > 0$, by Proposition 2 we have $\psi_1 = 0$, $\psi_2 = 0$, $\psi_3 > 0$, then we have

$$\int_0^t J(s)ds = \int_0^t w^T(s) \psi_3 w(s)ds,$$

thus, for $\forall t \in [0, T_f]$, we have

$$\int_0^{T_f} J(s)ds > \int_0^t J(s)ds \geq \frac{1}{b} x^T(t) P_i x(t) > 0,$$

it follows from (8) that

$$\begin{aligned} \int_0^{T_f} J(s)ds \geq &\frac{1}{b} x^T(t) P_i x(t) \geq x^T(t) D_i^T \psi_4 D_i x(t) \\ = &y^T(t) \psi_4 y(t), \end{aligned}$$

so we get

$$\int_0^{T_f} J(t)dt - \sup_{0 \leq t \leq T_f} y^T(t) \psi_4 y(t) \geq 0.$$

The proof is completed. □

Remark 2: This work focuses on achieving the finite-time boundedness and extended dissipative performance of switched linear systems and meanwhile save limited transmission resource. The event-triggered mechanism is adopted to determine the data sending, which effectively reduces the data transmission compared with periodic sampling. Frequent system switching is allowed over an event-triggered interval, which is different from the previous work [16] and [17] that only one switching happened over the event-triggered interval.

Theorem 2: If there exist positive scalars b, α, β and $\mu \geq 1$, positive definite matrices P_i, Q_i, Φ_i, such that the following matrix inequalities hold for all i, $j \in N$.

$$P_i \leq \mu P_j, \ \forall i \neq j,$$
$$\frac{1}{b} P_i - D_i^T \psi_4 D_i > 0,$$
$$\begin{bmatrix} \Lambda_{11} & -B_j Y_i & C_j & \hat{\Phi}_i \\ * & -\hat{\Phi}_i & 0 & -\hat{\Phi}_i \\ * & * & -Q_i & 0 \\ * & * & * & -\hat{\Phi}_i \end{bmatrix} < 0, \tag{30}$$
$$\Lambda_{11} = -\beta R_i + A_j R_i + B_j Y_i + R_i A_j^T + Y_i^T B_j^T,$$
$$\begin{bmatrix} \Gamma_{11} & -B_j Y_j & C_j & \hat{\Phi}_j \\ * & -\hat{\Phi}_j & 0 & -\hat{\Phi}_j \\ * & * & -Q_j & 0 \\ * & * & * & -\hat{\Phi}_j \end{bmatrix} < 0, \tag{31}$$
$$\Gamma_{11} = \alpha R_j + A_j R_j + B_j Y_j + R_j A_j^T + Y_j^T B_j^T,$$
$$\begin{bmatrix} \Delta_{11} & -B_j Y_i & C_j - R_i D_j^T \psi_2 & \hat{\Phi}_i & R_i D_j^T \\ * & -\hat{\Phi}_i & 0 & -\hat{\Phi}_i & 0 \\ * & * & -\psi_3 & 0 & 0 \\ * & * & * & -\hat{\Phi}_i & 0 \\ * & * & * & * & \psi_1^{-1} \end{bmatrix} < 0, \tag{32}$$
$$\Delta_{11} = -\beta R_i + A_j R_i + B_j Y_i + R_i A_j^T + Y_i^T B_j^T,$$
$$\begin{bmatrix} \Pi_{11} & -B_j Y_j & C_j - R_j D_j^T \psi_2 & \hat{\Phi}_j & R_j D_j^T \\ * & -\hat{\Phi}_j & 0 & -\hat{\Phi}_j & 0 \\ * & * & -\psi_3 & 0 & 0 \\ * & * & * & -\hat{\Phi}_j & 0 \\ * & * & * & * & \psi_1^{-1} \end{bmatrix} < 0, \tag{33}$$
$$\Pi_{11} = \alpha R_j + A_j R_j + B_j Y_j + R_j A_j^T + Y_j^T B_j^T$$

hold, the average dwell-time satisfies

$$\tau_a \geq \frac{ln\mu + (\alpha+\beta)T}{\alpha},$$

and

$$(\mu e^{(\alpha+\beta)T})^{N_0} e^{(\frac{ln\mu+(\alpha+\beta)T}{\tau_a} - \alpha)t} (\lambda_2 c_1 + \lambda_3 d) < \lambda_1 c_2,$$

$$(\mu e^{(\alpha+\beta)T})^{N_0} e^{(\frac{ln\mu+(\alpha+\beta)T}{\tau_a}-\alpha)t} < b,$$

we define

$$P_i^{-1} = R_i, \hat{\Phi}_i = R_i \Phi_i R_i, K_i R_i = Y_i,$$

and

$$\lambda_{min}(R^{-\frac{1}{2}} P_i R^{-\frac{1}{2}}) = \lambda_1, \lambda_{max}(R^{-\frac{1}{2}} P_i R^{-\frac{1}{2}}) = \lambda_2,$$
$$\lambda_{max}(R^{-\frac{1}{2}} Q_i R^{-\frac{1}{2}}) = \lambda_3.$$

Then the switched system (2) is finite-time boundedness with extended dissipative performance. The controller gains can be given by $K_i = Y_i R_i^{-1}$.

Proof: Similar to the proof of Theorem 1, we have

$$\dot{V}(t) - \beta V(t) - w^T(t) Q_i w(t) \leq X^T(t) \Omega_{ji} X(t).$$

Pre- and post-multiplying (30) by $diag\{P_i,\ P_i,\ I,\ P_i\}$, by Schur complement, we have $\Omega_{ji} < 0$, we can conclude that

$$\dot{V}(t) - \beta V(t) - w^T(t) Q_i w(t) < 0.$$

Similarly,

$$\dot{V}(t) - \beta V(t) - J(t) \leq X^T(t) \Phi_{ji} X(t).$$

Pre- and post-multiplying (32) by $diag\{P_i,\ P_i,\ I,\ P_i\}$, by Schur complement, we have $\Phi_{ji} < 0$, we can conclude that

$$\dot{V}(t) - \beta V(t) - J(t) < 0.$$

The following proof is similar to that of Theorem 1, it is omitted here. □

4. NUMERICAL EXAMPLE

Consider the switched linear system (2) with two subsystems.

$$A_1 = \begin{bmatrix} 2 & -4 \\ 1 & -3 \end{bmatrix},\ B_1 = \begin{bmatrix} 1 & -4 \\ -1 & 1 \end{bmatrix},\ C_1 = \begin{bmatrix} 3 & 2 \\ 0 & -1 \end{bmatrix},$$
$$D_1 = \begin{bmatrix} 0.02 & 0 \\ 0.02 & 0.02 \end{bmatrix};$$
$$A_2 = \begin{bmatrix} 1 & -6 \\ 3 & -2 \end{bmatrix},\ B_2 = \begin{bmatrix} 2 & -5 \\ -2 & 2 \end{bmatrix},\ C_2 = \begin{bmatrix} 1 & 2 \\ 0 & 2 \end{bmatrix},$$
$$D_2 = \begin{bmatrix} 0.02 & 0 \\ 0.01 & 0.01 \end{bmatrix}.$$

The initial condition is $x(0) = \begin{bmatrix} -0.2 & 0.2 \end{bmatrix}^T$, and $w(t) = \begin{bmatrix} e^{-t} * \sin(t) & e^{-t} * \cos(t) \end{bmatrix}^T$.

We choose $c_1 = 0.08$, $c_2 = 1$, $T_f = 8$, $\gamma = 0.6$, $u = 1$, $R = I_{2\times2}$, $b = 0.5$, $T = 0.2$, $G = 2$, $\varepsilon = 0.5$, $\alpha = 0.3$, $\beta = 0.3$, $\tau_a = 0.5$. For $(Q,\ S,\ R)$-dissipativity performance,we choose $Q = I_{2\times2}$, $S = I_{2\times2}$, $R = I_{2\times2}$.

Performance variable for each case is given in Table 1. By solving the LMIs in Theorem 2, we can obtain the controller gains and event-triggered parameters listed in Tables 2, 3 and 4, 5, respectively.

The switching signal of the system is given in Fig. 1. From Fig. 2, we can see that when $x^T(0)Rx(0) \leq 0.08$, the trajectory satisfies $x^T(t)Rx(t) \leq 1$, which demonstrates the finite-time boundedness of the closed loop system. Fig. 3 shows the event-triggered release instants and the inter-event intervals induced by the designed event-triggered mechanism. To focus on the inter-event intervals [0.6, 0.9] and [4.1, 4.4], it can be seen from Fig. 1 that frequent switching occurs in these intervals. This is different from the Fig.3 in the Reference [16] that at most one switching occurs in the inter-event intervals. Also, different from the Fig.4 in the Reference [5], we not only added the parameter $G = 2$ in the event-triggered mechanism which limits the upper bound of inter-event intervals but also added the parameter $T = 0.2$ in the event-triggered mechanism which limits the lower bound of inter-event intervals and meanwhile avoids the Zeno behavior.

Table 1. Performance variable for each case.

$L_2 - L_\infty$ performance,$\gamma^2 = 0.6$
H_∞ performance, $\gamma^2 = 0.6$
Passivity, $\gamma = 0.6$
Dissipativity, $\beta = 0.4$

Table 2. Controller gain for each case.

Subsystem 1
$L_2 - L_\infty$ performance, $K_1 = \begin{bmatrix} -0.4408 & 1.5744 \\ 0.8595 & -0.6980 \end{bmatrix}$
H_∞ performance, $K_1 = \begin{bmatrix} 5.2523 & 4.1620 \\ 6.1586 & 1.4482 \end{bmatrix}$
Passivity, $K_1 = \begin{bmatrix} 5.9603 & 3.9647 \\ 6.7264 & 1.4412 \end{bmatrix}$
Dissipativity, $K_1 = \begin{bmatrix} 246.9201 & 258.1637 \\ 196.0458 & 116.9295 \end{bmatrix}$

Table 3. Controller gain for each case.

Subsystem 2
$L_2 - L_\infty$ performance, $K_2 = \begin{bmatrix} 0.1064 & 0.3398 \\ 0.1673 & 0.0774 \end{bmatrix}$
H_∞ performance, $K_2 = \begin{bmatrix} 0.6618 & 1.2532 \\ 1.1050 & 0.1570 \end{bmatrix}$
Passivity, $K_2 = \begin{bmatrix} 2.2579 & 2.5304 \\ 2.5768 & 0.7323 \end{bmatrix}$
Dissipativity, $K_2 = \begin{bmatrix} 0.5085 & 1.0527 \\ 0.8948 & 0.1090 \end{bmatrix}$

Table 4. Event-triggered parameters for subsystem 1.

Subsystem 1
$L_2 - L_\infty$ performance, $\Phi_1 = \begin{bmatrix} 0.0010 & -0.0013 \\ -0.0013 & 0.0018 \end{bmatrix}$
H_∞ performance, $\Phi_1 = \begin{bmatrix} 0.0034 & 0.0004 \\ 0.0004 & 0.0003 \end{bmatrix}$
Passivity, $\Phi_1 = \begin{bmatrix} 0.0053 & 0.0005 \\ 0.0005 & 0.0004 \end{bmatrix}$
Dissipativity, $\Phi_1 = \begin{bmatrix} 0.0068 & 0.0033 \\ 0.0033 & 0.0028 \end{bmatrix}$

Table 5. Event-triggered parameters for subsystem 2.

Subsystem 2
$L_2 - L_\infty$ performance, $\Phi_2 = 10^{-8} * \begin{bmatrix} 0.2297 & -0.1481 \\ -0.1689 & 0.4135 \end{bmatrix}$
H_∞ performance, $\Phi_2 = \begin{bmatrix} 0.0011 & -0.0006 \\ -0.0006 & 0.0008 \end{bmatrix}$
Passivity, $\Phi_2 = \begin{bmatrix} 0.0022 & -0.0005 \\ -0.0005 & 0.0010 \end{bmatrix}$
Dissipativity, $\Phi_2 = \begin{bmatrix} 0.0026 & -0.0016 \\ -0.0016 & 0.0021 \end{bmatrix}$

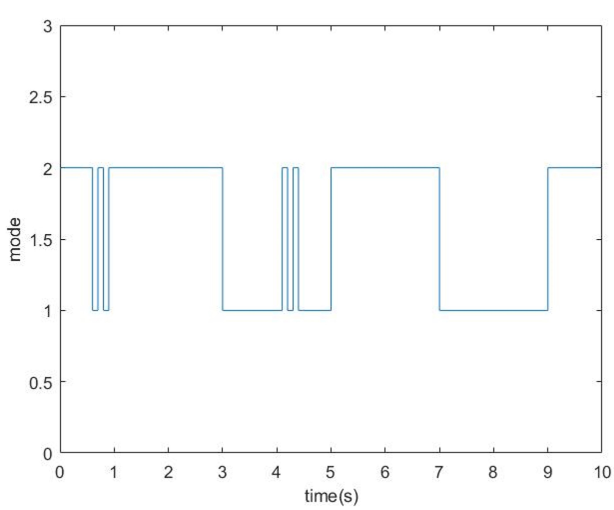


Fig. 1. The switching signal of the system.

5. CONCLUSION

In this paper, the problem of event-triggered finite time extended dissipative control for a class of switched linear systems with frequent asynchronism has been investigated. A novel event triggered method has been introduced. We can solve the H_∞, $L_2 - L_\infty$, Passivity and (Q, S,

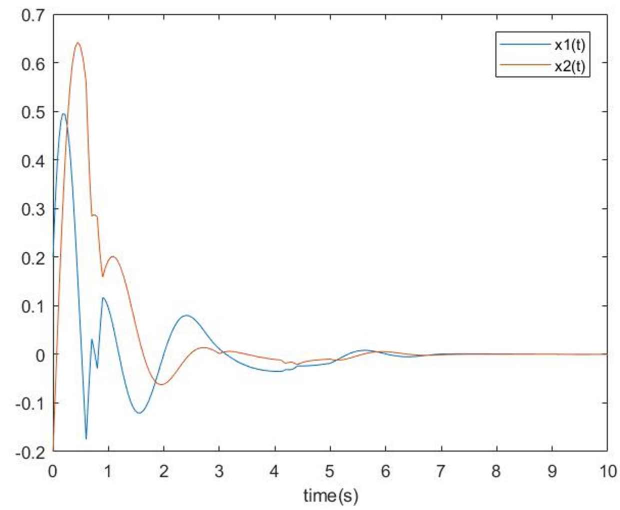


Fig. 2. The state trajectory under event triggered $L_2 - L_\infty$ control.

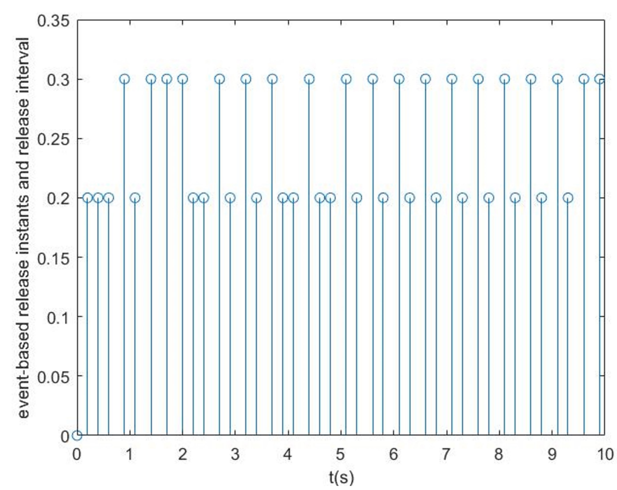


Fig. 3. Event triggered transmission interval.

R)-dissipativity performance in a unified framework based on extended dissipative. LMIs are used to obtain the results, we give numerical examples to show the effectiveness of the method.

REFERENCES

[1] S. Wang, T. G. Shi, L. X. Zhang, A. Jasra, and M. Zeng, "Extended finite-time H_∞ control for uncertain switched linear neutral systems with time-varying delays," *Neurocomputing*, vol. 152, pp. 377-387, 2015.

[2] Z. Xiang, Y. Sun, and M. S. Mahmoud, "Robust finite-time H_∞ control for a class of uncertain switched neutral systems," *Commun. Nonlinear Sci. Numer. Simul*, vol. 17, no. 4, pp. 1766-1778, 2012.

[3] L. X. Zhang, S. Zhuang, and R. D. Braatz, "Switched model predictive control of switched linear systems:Feasibility, stability and robustness," *Automatica*, vol. 67, pp. 8-21, 2016.

[4] X. D. Zhao, X. W. Liu, S. Yin, and H. Y. Li, "Improved results on stability of continuous-time switched positive linear systems," *Automatica*, vol. 50, pp. 614-621, 2014.

[5] Z. Y. Fei, C. X. Guan, and X. D. Zhao, "Event-triggered dynamic output feedback control for switched systems with frequent asynchronism," *IEEE Transactions on Automatic Control*, vol. 65, no. 7, pp. 3120-3127, 2020.

[6] H. Liu and X. Zhao, "Finite-time H_∞ control of switched systems with mode-dependent average dwell time," *Journal of the Franklin Institute*, vol. 351, pp. 1301-1315, 2014.

[7] X. Lin, H. Du, and S. Li, "Finite-time boundedness and L_2-gain analysis for switched delay systems with norm-bounded disturbance," *Appllied Mathmatics and Computation*, vol. 217, no. 12, pp. 5982-93, 2011.

[8] S. Wang, M. Basin, L. X. Zhang, M. Zeng, T. Hayat, and A. Alsaedi, "Reliable finite-time filtering for impulsive switched linear systems with sensor failures," *Signal Processing*, vol. 125, pp. 134-144, 2016.

[9] X. D. Zhao, P. Shi, and L. X. Zhang, "Asynchronously switched control of a class of slowly switched linear systems," *System and Control Letters*, vol. 61, pp. 1151-1156, 2012.

[10] H. L. Ren, G. D. Zong, and T. S. Li, "Event-triggered finite-time control for networked switched linear systems with asynchronous switching," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 48, no. 11, pp. 1874-1884, 2018.

[11] H. L. Ren, G. D. Zong, and H. R. Karimi, "Asynchronous finite-time filtering of networked switched systems and its application: an event-driven method," *IEEE Transactions on Circuits and Systems–I: Regular Papers*, vol. 66, no. 1, pp. 391-402, 2019.

[12] H. L. Ren, G. D. Zong, and C. K. Ahn, "Event-triggered finite-time resilient control for networked switched systems: An observer-based approach and its applications in a boost converter circuit system model," *Nonlinear Dynamics*, vol. 94, no. 4, pp. 2409-2421, 2018.

[13] B. Y. Zhang, W. X. Zheng, and S. Y. Xu, "Filtering of Markovian jump delay systems based on a new performance index," *IEEE Trans.Circuits Syst.I Reg.Pap*, vol. 60, pp. 1250-1263, 2013.

[14] H. Shen, Y. Z. Zhu, L. X. Zhang, and J. H. Park, "Extended dissipative state estimation for Markov jump neural networks with unreliable links,"*IEEE Trans. Neural Netw. Learning Syst*, vol. 28, pp. 346-358, 2017.

[15] T. H. Lee, M. J. Park, J. H. Park, and O. M. Kwon, "Extended dissipative analysis for neural networks with time-varying delays," *IEEE Trans. Neural Netw. Learn. Syst*, vol. 25, no. 10, pp. 1936-1941, 2014.

[16] X. Xiao, L. Zhou, and G. Lu, "Event-triggered H_∞ filtering of continuous time switched linear systems," *Signal Processing*, vol. 141, pp. 343-349, 2017.

[17] X. Q. Xiao, J. H. Park, and L. Zhou, "Event-triggered H_∞ filtering of discrete-time switched linear systems," *ISA Transactions*, vol. 77, pp. 112-121, 2018.

[18] X. H. Chang and G. H. Yang, "Nonfragile H_∞ filter design for T-S fuzzy systems in standard form," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 7, pp. 3448-3458, 2014.

[19] Z. M. Li, X. H. Chang, and J. H. Park, "Quantized static output feedback fuzzy tracking control for discrete-time nonlinear networked systems with asynchronous event-triggered constraints," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2019. DOI: 10.1109/TSMC.2019.2931530

[20] Y. G. Sun, Y. Z. Tian, and X. J. Xie, "Stabilization of positive switched linear systems and its application in consensus of multiagent systems," *IEEE Transactions on Automatic Control*, vol. 62, no. 12, pp. 6608-6613, 2017.

[21] Y. H. Ju and Y. G. Sun, "Stabilization of discrete-time switched positive linear systems via weak switched linear copositive Lyapunov function," *Automatica*, vol. 114, no. 3, p. 108836, 2020.

[22] Y. G. Sun, "Stability analysis of positive switched systems via joint linear copositive Lyapunov functions," *Nonlinear Analysis: Hybrid Systems*, vol. 19, pp. 156-152, 2016.

[23] J. Zhang and Y. G. Sun, "Reachable set estimation for switched nonlinear positive systems with impulse and time delay," *International Journal of Robust and Nonlinear Control*, vol. 30, no. 8, pp. 3332-3343, 2020.

[24] J. Zhang, Y. G. Sun, and F. W. Meng, "State bounding for discrete-time switched nonlinear time-varying systems using ADT method," *Applied Mathematics and Computation*, vol. 372, no. 125002, 2020.

[25] G. D. Zong, H. L. Ren, and H. R. Karimi, "Event-triggered communication and annular finite-time H_∞ filtering for networked switched systems," *IEEE Transactions on Cybernetics*, vol. 51, no. 1, pp. 309-317, 2021.

[26] X. W. Li, Z. Y. Sun, Y. Tang, and H. R. Karimi, "Adaptive event-triggered consensus of multi-agent systems on directed graphs," *IEEE Transactions on Automatic Control*, vol. 66, no. 4, pp. 1670-1685, 2021.

[27] W. Xiang and J. Xiao, "Stabilization of switched continuous-time systems with all modes unstable via dwell time switching," *Automatica*, vol. 50, no. 3, pp. 940-945, 2014.

[28] W. Xiang, "On equivalence of two stability criteria for continuous time switched systems with dwell time constraint," *Automatica*, vol. 54, pp. 36-40, 2015.

[29] W. Xiang, J. Xiao, and L. Han, "A new approach for stability analysis of time-dependent switched continuous-time linear systems," *Asian J. Control*, vol. 16, no. 2, pp. 431-468, 2014.

[30] W. Xiang, "Necessary and sufficient condition for stability of switched uncertain linear systems under dwell-time constraint," *IEEE Transactions on Automatic Control*, vol. 61, no. 11, pp. 3619-3624, 2016.

[31] J. Cheng, D. Zhang, W. Qi, J. Cao, and K. Shi, "Finite-time stabilization of T-S fuzzy semi-Markov switching systems: A coupling memory sampled-data control approach," *Journal of The Franklin Institute*, vol. 357, no. 16, pp. 11265-11280, 2020.

[32] J. Cheng, J. H. Park, X. Zhao, H. R. Karimi, and J. Cao, "Quantized nonstationary filtering of network-based Markov switching RSNSs: A multiple hierarchical structure strategy," *IEEE Transactions on Automatic Control*, vol. 65, no. 11, pp. 4816-4823, 2020.

[33] J. Cheng, J. H. Park, J. Cao, and W. Qi, "A hidden mode observation approach to finite-time SOFC of Markovian switching systems with quantization," *Nonlinear Dynamics*, vol. 100, pp. 509-521, 2020.

[34] Q. Zheng, S. Xu, and Z. Zhang, "Nonfragile quantized H_∞ filtering for discrete-time switched T-S fuzzy systems with local nonlinear models," *IEEE Transactions on Fuzzy Systems*, 2020. DOI: 10.1109/TFUZZ.2020.2979675

[35] S. Shi, Z. Y. Fei, T. Wang, and Y. L. Xu, "Filtering for switched T-S fuzzy systems with persistent dwell time," *IEEE Transactions on Cybernetics*, vol. 49, no. 5, pp.1923-1931, 2019.

[36] X. H. Chang and G. H. Yang, "Nonfragile H_∞ filtering of continuous-time fuzzy systems," *IEEE Transactions on Signal Processing*, vol. 59, no. 4, pp. 1528-1538, 2011.

[37] X. H. Chang, "Robust nonfragile H_∞ filtering of fuzzy systems with linear fractional parametric uncertainties," *IEEE Transactions on Fuzzy Systems*, vol. 20, no. 6, pp. 1001-1011, 2012.

[38] B. Wu, X. H. Chang, and X. D. Zhao, "Fuzzy H_∞ output feedback control for nonlinear NCSs with quantization and stochastic communication protocol," *IEEE Transactions on Fuzzy Systems*, 2020. DOI: 10.1109/TFUZZ.2020.3005342

[39] H. Li, Y. Zheng, and F. E. Alsaadi, "Algebraic formulation and topological structure of Boolean networks with state-dependent delay," *Journal of Computational and Applied Mathematics*, vol. 350, pp. 87-97, 2019.

[40] H. Li and Y. Wang, "Lyapunov-based stability and construction of Lyapunov functions for Boolean networks," *SIAM Journal on Control and Optimization*, vol. 55, no. 6, pp. 3437-3457, 2017.

[41] H. Li and X. Ding, "A control Lyapunov function approach to feedback stabilization of logical control networks," *SIAM Journal on Control and Optimization*, vol. 57, no. 2, pp. 810-831, 2019.

[42] H. Li, X. Xu, and X. Ding, "Finite-time stability analysis of stochastic switched Boolean networks with impulsive effect," *Applied Mathematics and Computation*, vol. 347, pp. 557-565, 2019.

[43] H. Li, X. Yang, and S. Wang, "Robustness for stability and stabilization of Boolean networks with stochastic function perturbations," *IEEE Transactions on Automatic Control*, vol. 66, no. 3, pp. 1231-1237, 2020.

[44] H. Li, X. Yang, and S. Wang, "Perturbation analysis for finite-time stability and stabilization of probabilistic Boolean networks," *IEEE Transactions on Cybernetics*, 2020. DOI: 10.1109/TCYB.2020.3003055

[45] H. Li, S. Wang, X. Li, and G. Zhao, "Perturbation analysis for controllability of logical control networks," *SIAM Journal on Control and Optimization*, vol 58, no. 6, pp. 3632-3657, 2020.

[46] H. Li, X. Ding, Q. Yang, and Y. Zhou, "Algebraic formulation and Nash equilibrium of competitive diffusion games," *Dynamic Games and Applications*, vol. 8, pp. 423-433, 2018.

[47] Y. Liu, Y. Zheng, H. Li, F. E. Alsaadi, and B. Ahmad, "Control design for output tracking of delayed Boolean control networks," *Journal of Computational and Applied Mathematics*, vol. 327, pp. 188-195, 2018.

[48] H. Li, Y. Wang, and P. Guo, "Output reachability analysis and output regulation control design of Boolean control networks," *Science China Information Sciences*, vol. 60, no. 2, pp. 022202, 2017.

[49] G. Zhao, Y. Wang, and H. Li, "A matrix approach to the modeling and analysis of networked evolutionary games with finite memories," *IEEE/CAA Journal of Automatica Sinica*, vol. 5, no. 4, pp. 818-826, 2018.

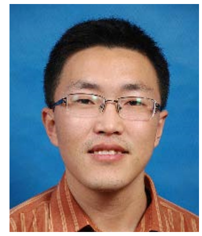
[50] Y. Li, H. Li, and X. Ding, "Set stability of switched delayed logical networks with application to finite-field consensus," *Automatica*, vol. 113, pp. 108768, 2020.

[51] Y. Li, H. Li, and W. Sun, "Event-triggered control for robust set stabilization of logical control networks," *Automatica*, vol. 95, pp. 556-560, 2018.

Hui Gao received his B.E degree from University of Jinan, Jinan, China, in 2015, and an M.S. degree in system science from Liaocheng University, Liaocheng, China, in 2018. He is currently working towards a Ph.D. degree in circuits and systems at the University of Electronic Science and Technology of China, Chengdu. His current research interests include switched systems, robust control and event-triggered control.

Kaibo Shi received his Ph.D. degree from the School of Automation Engineering, University of Electronic Science and Technology of China. He is a professor of School of Information Sciences and Engineering, Chengdu University. From September 2014 to September 2015, he was a visiting scholar at the Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada. He was a Research Assistant with the Department of Computer and Information Science, Faculty of Science and Technology, University of Macau, Taipa, from May 2016 to Jun 2016 and January 2017 to October 2017. He was also a Visiting Scholar with the Department of Electrical Engineering, Yeungnam University, Gyeongsan, Korea, from December 2019 to January 2020. His current research interests include stability theorem, robust control, sampled-data control systems, networked control systems, Lurie chaotic systems, stochastic systems and neural networks. He is the author or coauthor of over 60 research articles. He is a very active reviewer for many international journals.

Hongbin Zhang received his B.Eng. degree in aerocraft design from Northwestern Polytechnical University, Xian, China, in 1999, and his M.Eng. and Ph.D. degrees in circuits and systems from the University of Electronic Science and Technology of China, Chengdu, in 2002 and 2006, respectively. He has been with the School of Information and Communication Engineering, University of Electronic Science and Technology of China, since 2002, where he is currently a professor. From August 2008 to August 2010, he has served as a research fellow with the Department of Manufacturing Engineering and Engineering Management, City University of Hong Kong, Kowloon, Hong Kong. His current research interests include intelligent control, autonomous cooperative control and integrated navigation.



Jianwei Xia received his M.S. degree in automatic engineering from Qufu Normal University, Qufu, China, in 2004, and a Ph.D. degree in automatic control from the Nanjing University of Science and Technology, Nanjing, China, in 2007. He is a Professor with the School of Mathematics Science, Liaocheng University, Liaocheng, China. From 2010 to 2012, he was a Postdoctoral Research Associate with the School of Automation, Southeast University, Nanjing. From 2013 to 2014, he was a Postdoctoral Research Associate with the Department of Electrical Engineering, Yeungnam University, Gyeongsan, Korea. His current research interests include nonlinear system control, robust control, stochastic systems, and neural networks.etc.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.