Letter

Passivity-Based Stabilization for Switched Stochastic Nonlinear Systems

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Dear Editor,

This letter addresses the passivity-based mean square exponential stabilization problem for switched stochastic nonlinear systems. A concept of generalized small-time norm-observability is presented and an appropriate test condition is also provided. For pre-given passivity rate and average dwell time, a set of feedback controllers is designed by use of the passivity property. Then, combining with generalized small-time norm-observability, a sufficient condition to guarantee mean square exponential stabilization of a switched stochastic nonlinear system is given. As a special case, the switched stochastic linear system has also similar results. Finally, a numeral example shows the effectiveness of the proposed method.

Switched systems have attracted considerable attention in the last several decades [1]. Several methodologies have also been available in the study of switched systems, such as the common Lyapunov function method [2], the single Lyapunov function method, the multiple Lyapunov functions method [3], [4], the switched Lyapunov function method [5] and so on.

On the other hand, passivity, as a special kind of dissipativity, is an important tool in control study and the concept of passivity for switched systems is usually described by use of multiple storage functions, see for instance [6] and references therein. In [6], for pre-given average dwell time, feedback controllers have been designed to exponentially stabilize switched systems by using the passivity property of subsystems. Meanwhile, due to many practical applications, such as air traffic management, communication networks and health care systems etc., there have been increasing research activities in the field of stochastic systems [7]–[9]. Passivity is also usually used in the analysis and design of switched stochastic systems [10]–[12]. In real control process, to guarantee a specific dwell time, the dwell time switching method is a good choice. Recently, the dissipativity-based stabilization problem for switched stochastic systems was considered via the design of the sliding dynamics and a fuzzy-parameter-dependent filter in [7] and [13], respectively. Notice that, among the aforementioned literatures, the derived average dwell time is specifically determined by Lyapunov functions or storage functions, which cannot be designed arbitrarily. Moreover, the existing results on passivity for switched stochastic systems mainly focus on two aspects. One is the problem of passivity analysis and feedback passification for switched systems via designing a proper switching law or identifying a class of switching signals. The other is the passivity-based control and design problem for switched stochastic systems. Up to now, few works concentrate on the control and design problem by use of the passivity property of subsystems of switched stochastic systems.

In this letter, the passivity property of subsystems is used to address the mean square exponential stabilization problem for switched stochastic nonlinear systems, where one passive subsystem is necessary. The concept of small-time norm-observability is generalized and an appropriate test method is also provided. Finally, for any pre-given passivity rate and average dwell time, mean square exponential stability for switched stochastic systems is reached via the design of a set of controllers on the basis of the passivity property of subsystems.

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System description: Consider a switched stochastic nonlinear system

$$\begin{aligned} dx &= [f_{\sigma(t)}(x)+g_{\sigma(t)}(x)u_{\sigma(t)}]dt+l_{\sigma(t)}(x)d\omega \\ y &= h_{\sigma(t)}(x) \end{aligned} \tag{1}$$

where $x\in\mathbb{R}^n$ is the state, $\sigma:\mathbb{R}_+\to I=\{1,2,\ldots,q\}$ is a piecewise continuous function, called a switching signal, and $q>0$ is the number of subsystems. Furthermore, for $\forall i\in I$, $f_i(x)$, $g_i(x)$, $h_i(x)$, $l_i(x)$ are smooth functions satisfying $f_i(0)=0$, $h_i(0)=0$, $l_i(0)=0$. ω is a standard Wiener process on a complete probability space (Ω,F,P) with $E\{d\omega\}=0$ and $E\{d\omega^2\}=0$.

Preliminaries: In the following, we present several definitions and a lemma to develop the main result.

Definition 1 [14]: For a switching signal $\sigma(t)$ and $\forall t>\tau>0$, let $N_\sigma(\tau,t)$ denote the number of discontinuities of the switching signal $\sigma(t)$ on the interval (τ,t). If there exist numbers $\tau_a>0$ and $N_0\ge 0$ such that $N_\sigma(\tau,t)\le N_0+\frac{(t-\tau)}{\tau_a}$ holds, τ_a and N_0 are called the average dwell time and the chattering bound, respectively.

Definition 2 [7]: The equilibrium $x^*=0$ of the switched stochastic system (1) is said to be mean-square exponentially stable under $\sigma(t)$ if there exist $\eta>0$ and $\lambda>0$, such that for $\forall t>t_0$, $E\{\|x(t)\|^2\}\le \eta e^{-\lambda(t-t_0)}E\{\|x(t_0)\|^2\}$.

Definition 3 [9]: The ith subsystem of the switched system (1) is said to be passive with respect to the storage function $V_i(x)$, if there exists a function $V_i(x)\in C^2[\mathbb{R}^n,\mathbb{R}_+]$ with $V_i(0)=0$ such that

$$\mathcal{L}V_i(x)\le u_i^Ty_i,\ \forall(u_i,y_i)\in\mathbb{R}^m\times\mathbb{R}^m \tag{2}$$

where $\mathcal{L}V_i(\cdot)$ represents the infinitesimal generator defined by

$$\mathcal{L}V_i(x)=\frac{\partial V_i}{\partial x}[f_i(x)+g_i(x)u_i]+\frac{1}{2}tr[l_i^T(x)\frac{\partial^2 V_i}{\partial x^2}l_i(x)]. \tag{3}$$

Definition 4 [6]: For $\forall T_2>T_1\ge 0$, let $T_{p[T_1,T_2]}$ denote the total time when the passive subsystems are active on $[T_1,T_2]$ and $T_{n[T_1,T_2]}$ denotes the total time when the non-passive subsystems are active on $[T_1,T_2]$. Then, $\gamma=\frac{T_{p[T_1,T_2]}}{T_1-T_2}$ denote the passivity rate of the switched system, where $0<\gamma\le 1$.

Lemma 1 (KYP Lemma) [8]: The ith subsystem of the switched system (1) is passive if and only if there exists a function $V_i(x)\in C^2[\mathbb{R}^n,\mathbb{R}_+]$ with $V_i(0)=0$, such that

$$\frac{\partial V_i}{\partial x}f_i(x)+\frac{1}{2}tr[l_i^T(x)\frac{\partial^2 V_i}{\partial x^2}l_i(x)]\le 0 \tag{4}$$

$$\frac{\partial V_i}{\partial x}g_i(x)=h_i^T(x). \tag{5}$$

Generalized small-time norm-observability: To solve the passivity-based mean square stabilization problem for switched stochastic systems, a new concept of detectability or observability and a test method needs to be introduced.

Definition 5: A stochastic system

$$\begin{aligned} dx &= f(x)dt+l(x)d\omega \\ y &= h(x) \end{aligned} \tag{6}$$

is said to be generalized small-time norm-observable with degree $\bar\lambda$ if there exist $c>0$ and $\delta>0$ such that when $\|y(t+s)\|\le\delta$ holds for some $t\ge t_0$, $\tau>0$ and $\forall s\in[0,\tau]$, we have $E\{\|x(t+\tau)\|^2\}\le ce^{-\bar\lambda\tau}E\{\|x(t)\|^2\}$.

Remark 1: The generalized small-time norm-observability is a useful and special system property, which shows the relation of the state of the system (6) at instants t and $t+\tau$ when the norm of the system output is no more than a positive number δ on the time interval

$[t, t+\tau]$. It is worth noticing that this property does not mean that the trajectory of the system (6) is exponentially decreasing on $[t, t+\tau]$, and of course, that the system (6) is mean square exponentially stable. However, the converse is true, that is, exponential stability implies that the system is generalized small-time norm-observable.

Theorem 1: Suppose that there exists a function $W(x) \in C^2[\mathbb{R}^n, \mathbb{R}_+]$ with $W(0) = 0$ and constants $l_1 > 0$, $l_2 > 0$, $\delta > 0$ and $\bar{\lambda} > 0$, such that

$$\frac{\partial W}{\partial x} f(x) + \frac{1}{2} tr[l^T(x) \frac{\partial^2 W}{\partial x^2} l(x)] + (\delta + \bar{\lambda} - \|h(x)\|) W(x) \le 0$$
$$l_1 \|x\|^2 \le W(x) \le l_2 \|x\|^2$$

then, the system (6) is generalized small-time norm-observable with degree $\bar{\lambda}$.

Proof: According to Definition 5, to test the generalized small-time norm-observability property, we only have to show $E\{\|x(t^*+\tau)\|^2\} \le ce^{-\bar{\lambda}\tau} E\{\|x(t^*)\|^2\}$, when $\|h(x(t))\| \le \delta$ holds on the time interval $[t^*, t^*+\tau]$ for some $\tau > 0$, $t^* > 0$.

In view of (3), differentiating $W(x)$ along the trajectory of the system (7) gives

$$\mathcal{L}W(x) = \frac{\partial W}{\partial x} f(x) + \frac{1}{2} tr[l^T(x) \frac{\partial^2 W}{\partial x^2} l(x)] \le (-\delta - \bar{\lambda} + \|h(x)\|) W(x).$$

When $\|h(x(t))\| \le \delta$ holds on the time interval $[t^*, t^*+\tau]$ for some $\tau > 0$, $t^* > 0$, we can obtain

$$\mathcal{L}W(x) + \bar{\lambda} W(x) \le 0, \ t \in [t^*, t^*+\tau]. \tag{7}$$

Let $H(t) = e^{\bar{\lambda} t} W(x)$, $t \in [t^*, t^*+\tau]$, according to Itô's formula, we have

$$dH(t) = e^{\bar{\lambda} t}[\bar{\lambda} W(x) + \mathcal{L}W(x)]dt + e^{\bar{\lambda} t} \frac{\partial W(x)}{\partial x} l(x) d\omega. \tag{8}$$

By virtue of (7), integrating both sides of (8) from t^* to t and taking expectation yield $E\{H(t)\} \le E\{H(t^*)\}$, and then $E\{W(x(t))\} \le e^{-\bar{\lambda}(t-t^*)} E\{W(x(t^*))\}$. Furthermore, we can have $E\{\|x(t^*+\tau)\|^2\} \le ce^{-\bar{\lambda}\tau} E\{\|x(t^*)\|^2\}$, where $c = \frac{l_2}{l_1}$. By Definition 5, the system (6) is generalized small-time norm-observable with degree $\bar{\lambda}$. ■

Remark 2: Similar to Theorem 1, we also present a sufficient condition of generalized small-time norm-observability for the following stochastic linear system:

$$\begin{aligned} dx &= Axdt + Cxd\omega \\ y &= Dx. \end{aligned} \tag{9}$$

Suppose that there exist a positive definite matrix P and constants $\delta > 0$, $\bar{\lambda} > 0$, such that $2PA + C^T PC + (\delta + \bar{\lambda} - \|h(x)\|) P \le 0$. Then, the stochastic linear system (9) is generalized small-time norm-observable with degree $\bar{\lambda}$.

Main result: In this section, we will address the passivity-based mean square exponential stabilization problem for switched stochastic nonlinear systems by designing a set of controllers together with generalized small-time norm-observability. For simplicity, let I_p and I_n denote the index sets of passive and non-passive subsystems, respectively.

Theorem 2: Let $\gamma > 0$ and $\tau_a > 0$ be pre-given passivity rate and average dwell time, respectively. Suppose that there exist functions $V_i(x) \in C^2[\mathbb{R}^n, \mathbb{R}_+]$ with $V_i(0) = 0$ and constants $a_1 > 0$, $a_2 > 0$ and $\mu \ge 1$, such that

1) For $\forall i, j \in I$ and $\forall x \in \mathbb{R}^n$, the following conditions hold:

$$a_1 \|x\|^2 \le V_i(x) \le a_2 \|x\|^2$$
$$V_i(x) \le \mu V_j(x);$$

2) For $\forall i \in I_n$, there exists a positive constant λ_1, such that the ith subsystem with $u_i = 0$ satisfies $\mathcal{L}V_i(x) \le \lambda_1 V_i(x)$;

3) For $\forall i \in I_p$, the ith subsystem with $u_i = 0$ is generalized small-time norm-observable with degree $\bar{\lambda} \ge \lambda^*$, $c \le \frac{a_1}{a_2}$ and a constant $\delta > 0$, where

$$\lambda^* = \frac{\lambda_2}{\gamma} + \frac{ln\mu}{\gamma\tau_a} + \frac{\lambda_1}{\gamma} - \lambda_1$$

for some constant $\lambda_2 > 0$. Then, by designing the controllers

$$u_i = \begin{cases} -k_i(V_i(x), \tau_a)\left(\frac{\partial V_i(x)}{\partial x} g_i(x)\right)^T, & i \in I_p \\ 0, & i \in I_n \end{cases} \tag{10}$$

where

$$k_i(V_i(x), \tau_a) = \begin{cases} \lambda^* \left(\left\| \frac{\partial V_i(x)}{\partial x} g_i(x) \right\|^2 \right)^{-1} V_i(x), & \left\| \frac{\partial V_i(x)}{\partial x} g_i(x) \right\| > \delta \\ 0, & \left\| \frac{\partial V_i(x)}{\partial x} g_i(x) \right\| \le \delta \end{cases} \tag{11}$$

the switched stochastic system (1) is mean square exponentially stable under the passivity rate γ and any switching law with the dwell time τ_a.

Proof: Let $S_i = \{t : \|\frac{\partial V_i(x)}{\partial x} g_i(x)\| \le \delta\}$, $i \in I_P$. Next, the proof is split into two cases.

Case 1: $S_i = \emptyset$.

When the ith passive subsystem is active, according to Itô's formula, differentiating $V_i(x)$ along the trajectory gives $dV_i(x) = \mathcal{L}V_i(x)dt + \frac{\partial V_i(x)}{\partial x} l_i(x) d\omega$, where $\mathcal{L}V_i(x) = \frac{\partial V_i}{\partial x}(f_i(x) + g_i(x)u_i) + \frac{1}{2} tr[l_i^T(x) \frac{\partial^2 V_i}{\partial x^2} l_i(x)]$. In view of Definition 3, we have

$$\begin{aligned} \mathcal{L}V_i(x) + \lambda^* V_i(x) &= \frac{\partial V_i}{\partial x}(f_i(x) + g_i(x)u_i) + \frac{1}{2} tr[l_i^T(x) \frac{\partial^2 V_i}{\partial x^2} l_i(x)] \\ &\quad + \lambda^* V_i(x) \le u_i^T y_i + \lambda^* V_i(x) \\ &= -\lambda^* (\|\frac{\partial V_i(x)}{\partial x} g_i(x)\|^2)^{-1} V_i(x) \frac{\partial V_i(x)}{\partial x} g_i(x) \\ &\quad \times (\frac{\partial V_i(x)}{\partial x} g_i(x))^T + \lambda^* V_i(x) = 0 \end{aligned}$$

that is, $\mathcal{L}V_i(x) \le -\lambda^* V_i(x)$. Thus, we obtain

$$E\{V_{i_k}(x(t))\} \le \Psi_{i_k}(t, t_k) E\{V_{i_k}(x(t_k))\}$$
$$t \in [t_k, t_k+1), \ k = 0, 1, 2, \ldots$$

where

$$\Psi_{i_k}(t_k, t) = e^{\lambda_{i_k}(t-t_k)} = \begin{cases} e^{-\lambda^*(t-t_k)}, & i_k \in I_p \\ e^{\lambda_1(t-t_k)}, & i_k \in I_n. \end{cases} \tag{12}$$

For any given $t > t_0$, let $t_1, t_2, \ldots, t_k, \ldots, t_{N_\sigma(t_0,t)}$ be the switching instants on $[t_0, t]$, where $t_1 < t_2 < \cdots < t_k < \cdots < t_{N_\sigma(t_0,t)}$. A straightforward calculation shows that

$$\begin{aligned} E\{V_{i_{N_\sigma(t_0,t)}}(x(t))\} &\le \mu \Psi_{i_{N_\sigma(t_0,t)}}(t, t_{N_\sigma(t_0,t)}) E\{V_{i_{N_\sigma(t_0,t)-1}}(x(t_{N_\sigma(t_0,t)}))\} \\ &\le \mu^{N_\sigma(t_0,t)-1} e^{-\lambda^* T_p(t_1,t)} e^{\lambda_1 T_n(t_1,t)} E\{V_{i_1}(x(t_1))\} \\ &\le \mu^{N_\sigma(t_0,t)} e^{-\lambda^* T_p(t_1,t)} e^{\lambda_1 T_n(t_1,t)} \Psi_{i_0}(t_0, t_1) E\{V_{i_0}(x(t_0))\} \\ &= \mu^{N_\sigma(t_0,t)} e^{-\lambda^* T_p(t_0,t)} e^{\lambda_1 T_n(t_0,t)} E\{V_{i_0}(x(t_0))\} \\ &= a_2 e^{N_\sigma(t_0,t) ln\mu - \lambda^* \gamma(t-t_0) + \lambda_1(1-\gamma)(t-t_0)} E\{\|x(t_0)\|^2\} \\ &\le a_2 e^{(N_0 + \frac{t-t_0}{\tau_a}) ln\mu - \lambda^* \gamma(t-t_0) + \lambda_1(1-\gamma)(t-t_0)} E\{\|x(t_0)\|^2\} \\ &= a_2 \mu^{N_0} e^{-\lambda_2(t-t_0)} E\{\|x(t_0)\|^2\}. \end{aligned}$$

Using the condition 1) yields

$$E\{\|x(t)\|^2\} \le \frac{a_2}{a_1} \mu^{N_0} e^{-\lambda_2(t-t_0)} E\{\|x(t_0)\|^2\}.$$

Case 2: $S_i \neq \emptyset$.

According to KYP lemma, $\forall i \in I_p$, $\frac{\partial V_i(x)}{\partial x} g_i(x) = h_i^T(x)$ is continuous. Let $\{t : \|\frac{\partial V_i(x)}{\partial x} g_i(x)\| \le \delta\} = [t_{i_1}, t_{i_1'}] \bigcup [t_{i_2}, t_{i_2'}] \bigcup \cdots$. By using generalized small-time norm-observability, we have

$$E\{\|x(t_{i_k'})\|^2\} \le ce^{-\bar{\lambda}(t_{i_k'} - t_{i_k})} E\{\|x(t_{i_k})\|^2\} \le \frac{a_1}{a_2} e^{-\lambda^*(t_{i_k'} - t_{i_k})} E\{\|x(t_{i_k})\|^2\}.$$

From the condition 1), we obtain

$$\frac{1}{a_2} E\{V_i(x(t_{i_k'}))\} \le E\{\|x(t_{i_k'})\|^2\}$$
$$E\{\|x(t_{i_k'})\|^2\} \le \frac{1}{a_1} E\{V_i(x(t_{i_k'}))\}.$$

Then,

$$E\{V_i(x(t_{i'_k}))\} \le a_2 \frac{a_1}{a_2} e^{-\lambda^*(t_{i'_k}-t_{i_k})} E\{\|x(t_{i_k})\|^2\} \\ \le e^{-\lambda^*(t_{i'_k}-t_{i_k})} E\{V_i(x(t_{i_k}))\}.$$

Thus, when the passive subsystem is active on $[t_k, t_{k+1}]$, we can deduce that $E\{V_{i_k}(x(t_{k+1}))\} \le e^{-\lambda^*(t_{k+1}-t_k)} E\{V_{i_k}(x(t_k))\}$ hold. Similar to Case 1, we can also obtain

$$E\{\|x(t)\|^2\} \le \frac{a_2}{a_1} \mu^{N_0} e^{-\lambda_2(t-t_0)} E\{\|x(t_0)\|^2\}, \ \ \forall t > t_0.$$

Let $\eta = \frac{a_2}{a_1}\mu^{N_0}$, $E\{\|x(t)\|^2\} \le \eta e^{-\lambda_2(t-t_0)} E\{\|x(t_0)\|^2\}$. Hence, the resulting closed-loop system is mean square exponentially stable under any switching law with the average dwell time τ_a. ■

Illustrative example: In this section, a numerical example is given to illustrate the effectiveness of the proposed method.

Consider the switched stochastic nonlinear system of the form

$$dx = (f_i(x) + g_i(x)u_i)dt + l_i(x)d\omega \\ y = h_i(x) \tag{13}$$

where $i \in \{1,2\}$, ω is a standard Wiener process satisfying $E\{d\omega\} = 0$ and $E\{d\omega^2\} = 0$, and

$$f_1(x) = \begin{bmatrix} \frac{x_1}{2} + x_1x_2 \\ \frac{x_2}{3} - x_1^2 \end{bmatrix}, \ g_1(x) = \begin{bmatrix} 2 \\ 3 \end{bmatrix}, \quad l_1(x) = \begin{bmatrix} \sqrt{2}x_1 \\ -\sqrt{2}x_2 \end{bmatrix}$$

$$f_2(x) = \begin{bmatrix} -6x_1 + \frac{x_2}{3} \\ -5x_2 - \frac{x_1}{4} \end{bmatrix}, \ g_2(x) = \begin{bmatrix} -1 \\ 1 \end{bmatrix}, \ l_2(x) = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$h_1(x) = 7x_2, \ \ h_2(x) = -3x_1 + 4x_2.$$

According to the design strategy in Theorem 2, we can choose $\mu = e^2$, $\lambda_1 = 3$, $\delta = \frac{1}{30}$ and $\bar{\lambda} = 8$. It is worth pointing out that we can arbitrarily give the parameters γ and τ_a with $\gamma \in (\frac{\lambda_1}{\lambda_1+\bar{\lambda}}, 1]$ and $\tau_a > \frac{\ln\mu}{\bar{\lambda}}$. For the implementation of a specific simulation, we choose $\gamma = \frac{1}{2}$ and $\tau_a = 4$ as the passivity rate and the average dwell time, respectively. Then, we select $\lambda_2 = 1$, which in turn implies that $\lambda^* = 6$. Furthermore, the controllers are designed as follows:

$$u_i = \begin{cases} 0, & i = 1 \\ 0, & i = 2, \ |-3x_1 + 4x_2| \le \frac{1}{30} \\ \frac{9x_1^2 + 12x_2^2}{-3x_1 + 4x_2}, & i = 2, \ |-3x_1 + 4x_2| > \frac{1}{30}. \end{cases}$$

For the initial state $x(0) = (3, -5)$, the simulation results are shown in Figs. 1 and 2, which indicate that the resulting closed-loop system is mean square exponentially stable under a specific switching signal satisfying the dwell time $\tau_a = 4$.

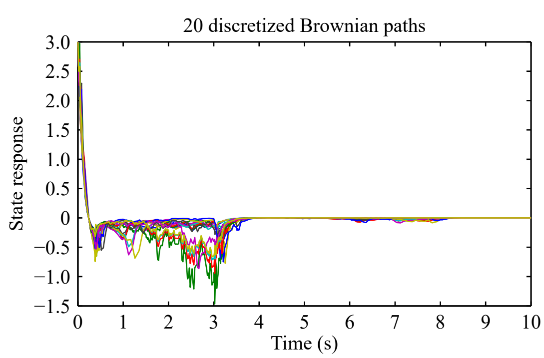

Fig. 1. The state response x_1.

Conclusion: In this letter, we provided a new observability concept–generalized small-time norm-observability and also gave a test method. For pre-given average dwell time and passivity rate, a sufficient condition has been obtained, under which switched stochastic nonlinear systems are mean square exponentially stable. In the future, how to get more desirable test method of generalized small-time norm-observability may be an interesting study direction.

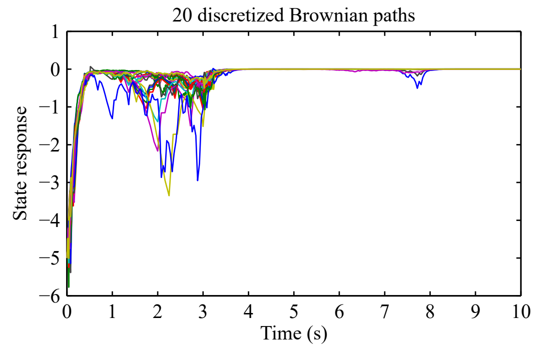

Fig. 2. The state response x_2.

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