STABILIZATION ON INPUT TIME-VARYING DELAY FOR LINEAR SWITCHED SYSTEMS WITH TRUNCATED PREDICTOR CONTROL

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Abstract. This study is concerned with the stabilization problem for input time-varying delay switched system under the truncated predictor control scheme. The delay in the prediction feedback, is subjected by predicting the future trajectory of the states by system equations and initial conditions, which is known as truncated prediction feedback (TPF). The TPF is used to construct the state feedback law for stabilizing the linear switched system. By constructing Lyapunov-Krasovskii functions and, the stability condition is derived to ensure the globally asymptotically stable of the state feedback stabilization at the origin. When switching system is unstable, truncated predictor control method and Hurwitz convex combination makes the system stable. Finally, a numerical example and their simulation results are given to show the effectiveness of the proposed approach.

1. Introduction. In the past decades, switching system have been widely studied by many researchers, which are special class of the hybrid system and it is mixture of discrete and continuous system and due to their applications in various fields such as switching and tuning paradigm from adaptive control [21], switched mode power supplies [23] and also in the control of mechanical systems [22], the automotive system[6], aircraft control design [4], switching power converters see [17] and the references therein.

On the other hand, many researchers have been focused the stabilization issues of the switched system with delay under the suitable control. Also, several results are investigated such as, the stochastic optimal control problem studied in [25] for a delayed Markov regime-switching jump-diffusion model and applications to finance. The optimal switching control control studied for horizontal (3-D) well’s path problem in [10] and in [31] obtained the required gradient of the cost function by using optimum control for time delay switched systems. Further, [14] investigated the stability analysis for uncertain switched time delay systems by using the sliding modes, in [34, 33] proved the robust stability and stabilization for uncertain impulsive switched systems by employing the delayed control and guaranteed cost control. In [32],

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the stabilization of the two dimensional switched system has been formulated by Fornasini-Marchesini for the local state-space model. In this stabilizing condition has been found using switched quadratic Lyapunov function of arbitrary switching signal. Then it has been developed to extend the average dwell time technique using the piecewise Lyapunov function for stabilizing two dimensional switching system except for some switching cases. In [37], they derived the stabilization condition for a single long time varying input delay linear system. The parametric Lyapunov equation method is used to stabilize the open loop system and also by truncating the predictor based control. Also the condition for closed loop system has been found. It tells about the semi-global stability condition by making system to magnitude saturation or energy constraints. In [26], stabilization is obtained by Hurwitz convex combination for the linear switching system with time varying delay. In this unknown constant acts as a delay bound of derivative. The stability of the delay bound system is obtained as a linear matrix inequality. In order to stabilize the switched system, the Hurwitz convex combination plays a major role not only in stability but also a smooth control Lyapunov function. The Hurwitz convex combination of the system matrices is characterized for the dynamic system which switch among a space model of family of positive state. For example, Bialas et.al., in [1] derived the sufficient and necessary condition for stability condition which is based on a Hurwitz convex combination in [3]. The conditions are given the simpler term by Stanislaw Bialas.

In delay differential equation, the time derivatives at the current time depend on the solution and possibly its derivatives at previous time. Time-delays appear in many engineering systems like water quality process [29], aircraft control [9] chemical control systems [28] and laser models [8] and references therein. Recently, the stabilization issue of time-delay switched system has been investigated based on Lyapunov Krasovskii functionals and LMI approach. Stability of time-delay has been traced back to the 18th century. In 1940s research on delay system has been begun in which frequency domain method was used. For explaining transfer function of the real world system was so difficult, so the time domain analysis has become famous. Recently so many results have been found in the time domain which was based on Lyapunov-Krasovskii stability theory, Razumikhin stability theorem, Halanay differential inequality, Barbatla lemma, comparison principle and so on. In [16] Lyapunov Krasovskii functionals was introduced, which is singular type complete quadratic Lyapunov Krasovskii functions with polynomial parameters. In [12, 13] quadratic Lyapunov Krasovskii functionals and simple Lyapunov Krasovskii functionals has been developed for finding stability condition for the time-delay system. One of the efficient method for the delay system to be stabilizes is the Lyapunov method. Krasovskii method of Lyapunov functionals [2, 20] and the Razumikhin method of Lyapunov functions [19] are the two important methods for the system involving time delay. In this we are using the Lyapunov Krasovskii method to stabilize the system, which cast the condition into linear matrix inequality (LMI). Asymptotic stability of a time-delay are guaranteed by the conditions on a Lyapunov-Krasovskii functional. Prediction feedback method has been paying more attention to the stabilization problem of input delay switched system. For practical implementation the predictor method brings difficulties [24, 18, 7, 27]. To eliminate the infinite dimension feedback laws, a finite dimensional predictor method was introduced which is TPF [15, 38, 37]. For open loop system TPF has been developed but it is not exponentially unstable [38, 15, 39]. Later in [35], TPF
for general open loop system including exponentially unstable has been proposed. In [30], they have consider the open loop system which has pure imaginary poles on the imaginary axis in which the general TPF for stabilization is not achieved for an arbitrarily large delay. But in closed-loop system asymptotic stability has been achieved. In [36], parametric Lyapunov equation has been used for stabilizing linear system with multiple delay in input. In which TPF law delay and TPF independent law were designed for the systems with open loop poles in the closed left half plane and system with open left half plane or at the origin. In [15, 38] low gain feedback design has been used. In [38] by considering low gain feedback design used for the parametric Lyapunov equation and this is termed as TPF.

The motivations by the above discussion, there are two kinds of feedback controllers are studied for time delay systems, that is, finite dimensional controller (allow finite delay) and infinite dimensional controller (allow arbitrarily large delay). The TPF is designed either finite or infinite dimensional controller. In particular, the infinite dimensional TPF is very hard to apply the physical phenomenons. Therefore, the physical implementation necessity, we design the finite dimensional TPF for a linear switching system with time-varying input delay. The controller equation for the feedback gain $K_i$ simplifies to $u(t) = K_i e^{A_i(\psi(t) - t)} x(t)$ for all $t \geq 0$ [39]. We find the less sufficient condition for asymptotic stabilization of linear switching system under the TPF can be established with the aid of Lyapunov-Krasovskii stability method and Hurwitz convex combination. Finally, numerical example shows that the effectiveness of the derived results. This paper is organized as: In section-II, it speaks about the preliminaries required for the stability analysis. In section-III we derive the stabilization results and Section-IV derived the numerical stimulation to validate the derived theorem.

2. Preliminaries. Consider switching systems in the presence of a time-varying input delay,

$$
\begin{align*}
\dot{x}(t) &= A_{\sigma(t)} x(t) + B_{\sigma(t)} u(\psi(t)), \\
y(t) &= C_{\sigma(t)} x(t),
\end{align*}
$$

(1)

where $x \in \mathbb{R}^n, y \in \mathbb{R}^n$, is the state $u \in \mathbb{R}^n$ is the input, $\sigma(t) : [0, \infty) \rightarrow M = 1, 2, \ldots, m$ is the switching signal which is depending on time $t$ or state $x(t)$; $\psi(t) : \mathbb{R} \rightarrow \mathbb{R}$ is a continuously differentiable function with delay, $A_i \in \mathbb{R}^{n \times n}, B_i \in \mathbb{R}^{n \times p}, C_i \in \mathbb{R}^{q \times n}$ are constant matrices.

The function $\psi(t)$ is given by $\psi(t) = t - d(t), \quad (2)$ where $d(t) \geq 0$ is the time-varying delay. From (1), we understand that the predictor design is given by $\psi(t)$.

**Hurwitz convex combination condition:** We should assume that there exists a Hurwitz linear convex combination $F$ of $A_i + B_i K_i$ i.e.,

$$
F = \sum_{i=1}^{m} \alpha_i (A_i + B_i K_i), \quad \text{where} \quad 0 < \alpha_i < 1 \quad \text{and} \sum_{i=1}^{m} \alpha_i = 1.
$$

Since $F$ is Hurwitz there exists a matrix $P > 0$ such that $F^T P + PF = -Q$, for a given positive definite matrix $Q$. To make particular quadratic form negative from the sub-region, which is obtain by dividing $\mathbb{R}^n$ into $N$ sub-regions. This act as one
of the sufficient condition for Hurwitz stability of the convex combination of two matrices.

The switching region and law for the given $P$ and $Q$ is given by,

$$\tau_i = \{ x \in \mathbb{R}^n | x^T[(A_i + B_i K_i)^T P + P(A_i + B_i K_i)] x \leq -x^T Q x \},$$

$$\bar{\tau}_i = \{ x \in \mathbb{R}^n | x^T[(A_i + B_i K_i)^T P + P(A_i + B_i K_i)] x \leq -\frac{1}{\zeta} x^T Q x \},$$

for each $i \in M$ where $M = 1, 2, 3 \ldots m$.

$$R^m = \bigcup_{i=1}^m \bar{\tau}_i.$$  \hspace{1cm} (5)

The switching region is constructed by:

$$\bar{\tau}_1 = \tau_1, \bar{\tau}_2 = \tau_2 / \tau_1 \cap \bar{\tau}_1, \ldots, \bar{\tau}_i = \tau_i / \tau_i \cap \bigcup_{j=1}^{i-1} \bar{\tau}_j, \ldots, \bar{\tau}_m = \tau_m / \tau_m \cap \bigcup_{j=1}^{m-1} \bar{\tau}_j.$$

Thus $\bigcup_{j=1}^m \bar{\tau}_i = R^n$ and $\bar{\tau}_i \cap \bar{\tau}_j = \emptyset$. The switching law is given as $\sigma(t) = i$ when $x(t) \in \bar{\tau}_i$. Asymptotical stability of the system $x'(t) = (A_i + B_i K_i)x(t)$ is guarantee by the presence of Hurwitz convex combination under the switching law.

Switching rule:

The minimum rule is used to determine the next mode at each switching

$$p(x(t)) = \arg \min \{ x^T(t)((A_i + B_i K_i)^T P + P(A_i + B_i K_i))x(t) \}. \hspace{1cm} (6)$$

**Remark 1.** When $x(t) \in \bar{\tau}_i$ from $\sigma(t) = i$, then the $i^{th}$ subsystem is active.

**Assumption 1.** The continuous differentiable function $\psi(t)$ which is also invertible such that

$$0 < \beta \leq \psi'(t) < \infty,$$

for a finite number $h \geq 0$ such that $\forall t \geq 0$,

$$0 \leq d(t) \leq h. \hspace{1cm} (7)$$

The analytical solution of (1) can be computed as

$$x(t) = e^{A_i(t-\psi(t))} + \int_{\psi(t)}^{t} e^{A_i(t-s)} B_i u(s) ds. \hspace{1cm} (8)$$

**Lemma 2.1.** [11] For a function $x : [a, b] \rightarrow \mathbb{R}^n$, with $a, b \in \mathbb{R}$ and $b > a$, let $Q$ be a positive definite matrix, then the inequality is stated by

$$\left( \int_a^b x(t) dt \right) Q \left( \int_a^b x(t) dt \right) \leq (b-a) \int_a^b x(t) Q x(t) dt. \hspace{1cm} (9)$$

**Lemma 2.2.** [5] Let $P$ be a positive definite matrix, then the identity holds

$$e^{A_i t} P e^{A_i t} - e^{\omega_i t} P = -e^{\omega_i t} \int_0^t e^{-\omega_i \tau} e^{A_i \omega_i} R e^{A_i \omega_i} d\omega_i,$$

where $\omega_i \geq 0$ is a scalar and

$$R = -A_i^T P - PA_i + \omega_i P.$$

Also, $R$ is a positive definite then

$$e^{A_i t} P e^{A_i t} \leq e^{\omega_i t} P. \hspace{1cm} (10)$$
3. Stabilization Results. For $\sigma(t) = i$, the control structure for the system (1) with Assumption 1 is given as

$$u(t) = K_i e^{A_i(\psi(t)-t)}x(t),$$

where $K_i$ is a control gain matrix.

Considering solution (8) and also by TPF control law (11) can be derived as

$$x'(t) = A_i x(t) + B_i K_i e^{A_i(t-\psi(t))}x(\psi(t))$$
$$= (A_i + B_i K_i)x(t) - B_i K_i \lambda(t),$$

where

$$\lambda(t) = \int_{\psi(t)}^{t} e^{A_i(t-s)} B_i K_i e^{A_i(s-\psi(s))}x(\psi(s))ds.$$

**Theorem 3.1.** The TPF control law globally asymptotically stabilizes the system at the origin by considering the switching system which satisfies the assumption 1, there exist constants $\rho > 0$ and $\omega_i \geq 0$, $P > 0, Q > 0$ such that

$$B_i B_i^T \leq \rho P^{-1},$$

$$(A_i - \frac{1}{2} \omega_i I)^T + (A_i - \frac{1}{2} \omega_i I) < 0,$$

$$F_i^T P + PF_i < 0,$$

$$\left[ \begin{array}{cc} \gamma I + \eta P - \frac{1}{P} Q & P \\ P & -\frac{1}{P^2} I \end{array} \right] < 0,$$

where $\gamma = 2\rho^2 h^2 e^{2\omega_i/h} \beta^{-1}$. Then the linear switching system is globally asymptotically stable.

**Proof.** Let the Lyapunov function is given by

$$V_0(x(t)) = x^T(t)Px(t).$$

Along the trajectories, the time derivative for $V_0(x(t))$ is given by

$$V_0'(x(t)) = 2x^T(t)Px'(t)$$
$$= 2x^T(t)P[A_i + B_i K_i]x(t) - 2x^T(t)PB_i K_i \lambda(t)$$
$$= x^T(t)P[A_i + B_i K_i]x(t) + x^T(t)[A_i + B_i K_i]TPx(t) - 2x^T(t)PB_i K_i \lambda(t)$$
$$= x^T(t)P[A_i + B_i K_i]x(t) + x^T(t)[A_i + B_i K_i]TPx(t)$$
$$- x^T(t)(PB_i K_i K_i^T B_i^T P)x(t) + ||\lambda(t)||^2$$
$$\leq x^T(t)(-\frac{1}{\zeta} Q)x(t) - x^T(t)(PB_i K_i K_i^T B_i^T P)x(t) + ||\lambda(t)||^2$$
$$\leq x^T(t)(-\frac{1}{\zeta} Q - PB_i K_i K_i^T B_i^T P)x(t) + ||\lambda(t)||^2,$$

by using lemma 2.2 and $\lambda(t)$, we have,

$$||\lambda(t)||^2$$
$$\leq (t - \psi(t)),$$

$$\int_{\psi(t)}^{t} x^T(\psi(s)) e^{A_i(t-\psi(s))} K_i^T B_i^T e^{A_i(t-s)} B_i K_i e^{A_i(s-\psi(s))}x(\psi(s))ds$$
\[ \leq d(t) \int_{\psi(t)}^{t} x^T(\psi(s))e^{A_s^T(s-\psi(s))} \]

\[ \cdot P B_i B_i^T e^{A_s^T(t-s)} B_i B_i^T P e^{A_s^T(s-\psi(s))} x(\psi(s)) ds \]

\[ \leq h \int_{\psi(t)}^{t} x^T(\psi(s))e^{A_s^T(s-\psi(s))} e^{A_s^T(t-s)} e^{A_s^T(t-\psi)} \left( B_i B_i^T P \right)^2 e^{A_s^T(s-\psi(s))} x(\psi(s)) ds, \]

where the condition \( B_i B_i^T \leq \rho P^{-1} \) and \( K = -B_i^T P \) has been used

\[ \leq \left( \rho \right)^2 h \int_{\psi(t)}^{t} x^T(\psi(s))e^{\omega(t-s)} e^{\omega(s-\psi(s))} x(\psi(s)) ds \]

\[ \leq \rho^2 h e^{2\omega \cdot h} \int_{\psi(t)}^{t} x^T(\psi(s)) x(\psi(s)) ds. \]

Let us change the variable \( \tau = \psi(s), ds = (d/ds(\psi(s)))_{s=\psi^{-1}(\tau)}^{-1} d\tau. \)

\[ ||\lambda(t)||^2 \leq \rho^2 h e^{2\omega \cdot h} \int_{\psi(t)}^{\psi(\psi(t))} x^T(\tau) x(\tau) (d/ds(\psi(s)))_{s=\psi^{-1}(\tau)}^{-1} d\tau \]

\[ \leq \rho^2 h e^{2\omega \cdot h} \int_{\psi(t)}^{\psi(t)} x^T(\tau) x(\tau) d\tau \]

\[ \leq \rho^2 h e^{2\omega \cdot h} \int_{\psi(t)}^{\psi(t)} x^T(\tau) x(\tau) d\tau. \]

Two krasovskii functional for the terms \( ||\lambda(t)||^2 \) is considered as follows:

\[ V_1(x_t) = \rho^2 h e^{2\omega \cdot h} \int_{0}^{\psi(t)} \left( \int_{t-s}^{t} x^T(\tau) x(\tau) d\tau \right) ds, \]

where \( x_t(\theta) = x(t+\theta), \theta \in [-2h, 0]. \)

\[ V_1(x_t) = 2 \rho^2 h^2 e^{2\omega \cdot h} \int_{0}^{\psi(t)} \left( \int_{t-s}^{t} x^T(\tau) x(\tau) d\tau \right) ds - \rho^2 h e^{2\omega \cdot h} \int_{t-2h}^{t} x^T(\tau) x(\tau) d\tau. \]

Lyapunov-Krasovskii functional’s derivative is Lyapunov-Krasovskii functional’s derivative is \( V(x_t) = V_0(x(t)) + V_1(x_t), \) then we obtain

\[ V'(x(t)) \]

\[ = V_0'(x(t)) + V_1'(x_t) \]

\[ \leq x^T(t) \left( -\frac{1}{\zeta} Q x(t) - \| P_i B_i K_i^T B_i^T P \| x(t) + \rho^2 h e^{2\omega \cdot h} \int_{t-2h}^{t} x^T(\tau) x(\tau) d\tau \right) \]

\[ + 2 \rho^2 h^2 e^{2\omega \cdot h} \int_{t-2h}^{t} x^T(\tau) x(\tau) d\tau \]

\[ \leq x^T(t) \left( -\frac{1}{\zeta} Q x(t) - x^T(t) (P \rho)^2 x(t) + 2 \rho^2 h^2 e^{2\omega \cdot h} \int_{t-2h}^{t} x^T(\tau) x(\tau) d\tau \right) \]

\[ \leq x^T(t) \left[ -\frac{1}{\zeta} Q - (\rho P)^2 + \gamma I \right] x(t), \]

where \( \gamma = 2 \rho^2 h^2 e^{2\omega \cdot h} \) and take \( -\frac{1}{\zeta} Q - (\rho P)^2 + \gamma I \leq -\eta P, \) then we have

\[ V'(x(t)) \leq -x^T(t) \eta P x(t) \]
Example. Consider the class of switching system with unstable subsystems

\[
\begin{align*}
\dot{x}(t) &= A_i x(t) + B_i u(t), \quad i = 1, 2, \\
y(t) &= C_i x(t),
\end{align*}
\]

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

\[
A_1 = \begin{pmatrix} 3 & 2 \\ -5 & -1 \end{pmatrix}; B_1 = \begin{pmatrix} -1 & 0 \\ 1 & -1 \end{pmatrix};
A_2 = \begin{pmatrix} -1 & 20 \\ -2 & 2 \end{pmatrix}; B_2 = \begin{pmatrix} 1 & 1 \\ 0 & -1 \end{pmatrix}.
\]

The linear system \( x'(t) = A_1 x(t) \) and \( x'(t) = A_2 x(t) \) are unstable see figure 1 and figure 2.

\( K_1 \) and \( K_2 \) has been chosen as

\[
K_1 = \begin{pmatrix} -2.5 & 1 \\ 5 & 0.5 \end{pmatrix}; K_2 = \begin{pmatrix} -3 & -14 \\ 2 & 4 \end{pmatrix}.
\]

The convex combination \( F \), which is designed using the switching law

\[
F = \frac{1}{3}(A_1 + B_1 K_1) + \frac{2}{3}(A_2 + B_2 K_2) = \begin{pmatrix} -5/3 & -21/3 \\ -20.5/3 & -3.5/3 \end{pmatrix},
\]

this shows that \( F \) is Hurwitz. Taking \( \omega_i = -2, \rho = 0.05, h = 0.03, \beta^{-1} = 1, \gamma = 2\rho h^2 e^{2\omega h} \beta^{-1} = 3.9911 e^{-6} \).

And \( \zeta = 10^4 \) and choosing \( d(t) = 0.008 - 0.008 \sin(t) \) solving LMI’s (14) in the theorem 3.1 condition leads to matrix

\[
P = \begin{pmatrix} 0.0457 & 0.0064 \\ 0.0064 & 0.0465 \end{pmatrix}.
\]

Thus

\[
Q = 1.0 e^{0.3} \begin{pmatrix} 2.1127 & -0.0004 \\ -0.0004 & 2.1006 \end{pmatrix}.
\]

The switching region \( (4) \) for the model and mode 2 with the given \( P \) and \( Q \)

\[
\tau_1 = \{ x \in R^2 : -0.1572x_1^2 - 1.6932x_1 x_2 - 0.442x_2^2 \leq 0.21127x_1^2 - 0.00008x_1 x_2 + 0.21006x_2^2 \},
\]

\[
\tau_2 = \{ x \in R^2 : -0.234x_1^2 + 0.4908x_1 x_2 - 0.058x_2^2 \leq 0.21127x_1^2 - 0.00008x_1 x_2 + 0.21006x_2^2 \},
\]

and \( R^2 = \tau_1 \cup \tau_2 \). Hence globally asymptotically stability of the linear switched system has been established. Further, we choose the initial condition \( x(t) = [0.3 \ 0.1]^T \) then we get the phase plot and stability behavior of system (16). The phase plot for the mode:1 and mode:2 of system (16) show the Figure:3, Figure:4 and the stability for the mode:1 and mode:2 of system (16) show the Figure:5, Figure:6, respectively.
Remark 3. The main contribution of this work is given below:
1. We designed the finite dimensional TPF for a linear switching system with time-varying input delay.
2. We found less sufficient condition for asymptotic stabilization of linear switching system under the TPF can be established with the aid of Lyapunov-Krasovskii stability method and Hurwitz convex combination.

5. Conclusion. In this paper, we investigated the truncated predictor control for linear switched systems with input time-varying delay and we obtained some sufficient condition for globally asymptotic stability in the method of LMI by using the Truncated Predictor control and Hurwitz convex combination. Finally, we showed
the numerical example for unstable sub-systems are globally asymptotically stabilized, it gave the clear idea to develop the truncated predictor control in linear switched systems with input time-varying delays. Moreover, the input time varying delay allow the uncertainty, the emerging real-world necessity we will develop the TPF for uncertain linear and nonlinear switched system in future.

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REFERENCES

[1] B. Aguirre-Hernández, F. R. García-Sosa, C. A. Loredo-Villalobos, R. Villafuerte-Segura and E. Campos-Cantón, Open problems related to the hurwitz stability of polynomials segments, Mathematical Problems in Engineering, 9-10 (2018), 1–8.

[2] Y. Ariba and F. Gouaisbaut, Construction of lyapunov-krasovskii functional for time-varying delay systems, in 2008 47th IEEE Conference on Decision and Control, IEEE, (2008), 3995–4000.

[3] S. Bialas, A sufficient condition for hurwitz stability of the convex combination of two matrices, Control and Cybernetics, 33 (2004), 109–112.

[4] J. D. Boskovic and R. K. Mehra, A multiple model-based reconfigurable flight control system design, in Proceedings of the 37th IEEE Conference on Decision and Control (Cat. No. 98CH36171), vol. 4, IEEE, (1998), 4503–4508.

[5] Z. Ding and Z. Lin, Truncated state prediction for control of lipschitz nonlinear systems with input delay, in 53rd IEEE Conference on Decision and Control, IEEE, (2014), 1966–1971.

[6] A. Emadi, A. Khaligh, C. H. Rivetta and G. A. Williamson, Constant power loads and negative impedance instability in automotive systems: definition, modeling, stability, and control of power electronic converters and motor drives, IEEE Transactions on Vehicular Technology, 55 (2006), 1112–1125.

[7] K. Engelborghs, M. Dambrine and D. Roose, Limitations of a class of stabilization methods for delay systems, IEEE Transactions on Automatic Control, 46 (2001), 336–339.

[8] T. Erneux, J. Javaloyes, M. Wolfrum and S. Yanchuk, Introduction to focus issue: Time-delay dynamics, Chao, 27 (2017), 114201.

[9] R. Francisco, F. Mazenc and S. Mondié, Global asymptotic stabilization of a pvtol aircraft model with delay in the input, in Applications of Time Delay Systems, Springer, (2007), 343–356.

[10] Z. Gong, K. L. Teo, C. Liu and E. Feng, Horizontal well’s path planning: An optimal switching control approach, Applied Mathematical Modelling, 39 (2015), 4022–4032.

[11] K. Gu, An integral inequality in the stability problem of time-delay systems, in Proceedings of the 39th IEEE Conference on Decision and Control (Cat. No. 00CH37187), vol. 3, IEEE, (2000), 2805–2810.

[12] K. Gu, J. Chen and V. L. Kharitonov, Stability of Time-Delay Systems, Springer Science & Business Media, 2003.

[13] K. Gu and S.-I. Niculescu, Survey on recent results in the stability and control of time-delay systems, Journal of Dynamic Systems, Measurement, and Control, 125 (2003), 158–165.

[14] M. H. H. Kani, M. J. Yu danpannah and A. H. Markazi, Stability analysis of a class of uncertain switched time-delay systems with sliding modes, International Journal of Robust and Nonlinear Control, 29 (2019), 19–42.

[15] Z. Lin and H. Fang, On asymptotic stabilizability of linear systems with delayed input, IEEE Transactions on Automatic Control, 52 (2007), 998–1013.

[16] L.-L. Liu, J.-G. Peng and B.-W. Wu, On parameterized lyapunov–krasovskii functional techniques for investigating singular time-delay systems, Applied Mathematics Letters, 24 (2011), 703–708.

[17] D. Ma, W.-H. Ki and C.-Y. Tsui, A pseudo-ccm/dcm simo switching converter with freewheel switching, IEEE Journal of Solid-State Circuits, 38 (2003), 1007–1014.

[18] A. Manitius and A. Olbrot, Finite spectrum assignment problem for systems with delays, IEEE Transactions on Automatic Control, 24 (1979), 541–552.

[19] F. Mazenc and M. Malisoff, Extensions of razumikhin theorem and lyapunov–krasovskii functional constructions for time-varying systems with delay, Automatica, 78 (2017), 1–13.

[20] F. Mazenc, S.-I. Niculescu and M. Krstic, Lyapunov–krasovskii functionals and application to input delay compensation for linear time-invariant systems, Automatica, 48 (2012), 1317–1323.

[21] K. S. Narendra, O. A. Driollet, M. Feiler and K. George, Adaptive control using multiple models, switching and tuning, International Journal of Adaptive Control and Signal Processing, 17 (2003), 87–102.

[22] A. R. Oliveira, S. B. Gonçalves, M. de Carvalho and M. T. Silva, Development of a musculo-tendon model within the framework of multibody systems dynamics, in Multibody Dynamics, Springer, (2016), 213–237.
[23] V. Pinon, F. Hasbani, A. Giry, D. Pache and C. Garnier, A single-chip wcdma envelope reconstruction ldmos pa with 130mhz switched-mode power supply, in 2008 IEEE International Solid-State Circuits Conference-Digest of Technical Papers, IEEE, (2008), 564–636.

[24] L. Rodríguez-Guerrero, A. Ramirez and C. Cuvas, Predictive control and truncated predictor: A comparative study on numerical benchmark problems, in 2014 11th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE), IEEE, (2014), 1–6.

[25] E. Savku and G.-W. Weber, A stochastic maximum principle for a markov regime-switching jump-diffusion model with delay and an application to finance, Journal of Optimization Theory and Applications, 179 (2018), 696-721.

[26] X.-M. Sun, W. Wang, G.-P. Liu and J. Zhao, Stability analysis for linear switched systems with time-varying delay, IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), 38 (2008), 528–533.

[27] V. Van Assche, M. Dambrine, J.-F. Lafay and J.-P. Richard, Some problems arising in the implementation of distributed-delay control laws, in Proceedings of the 38th IEEE Conference on Decision and Control (Cat. No. 99CH36304), vol. 5, IEEE, (1999), 4668–4672.

[28] R. A. van Santen, Role of time delay in chemical reaction rates, The Journal of Chemical Physics, 57 (1972), 5418–5426.

[29] D. Wang, P. Shi, W. Wang and H. R. Karimi, Non-fragile $h_{\infty}$ control for switched stochastic delay systems with application to water quality process, International Journal of Robust and Nonlinear Control, 24 (2014), 1677–1693.

[30] Y. Wei and Z. Lin, On the delay bounds of linear systems under delay independent truncated predictor feedback: the state feedback case, in 2015 54th IEEE Conference on Decision and Control (CDC), IEEE, (2015), 4642–4647.

[31] C. Wu, K. L. Teo, R. Li and Y. Zhao, Optimal control of switched systems with time delay, Applied Mathematics Letters, 19 (2006), 1062–1067.

[32] L. Wu, R. Yang, P. Shi and X. Su, Stability analysis and stabilization of 2-d switched systems under arbitrary and restricted switchings, Automatica, 59 (2015), 206–215.

[33] H. Xu and K. L. Teo, Robust stabilization of uncertain impulsive switched systems with delayed control, Computers & Mathematics with Applications, 56 (2008), 63–70.

[34] H. Xu, K. L. Teo and X. Liu, Robust stability analysis of guaranteed cost control for impulsive switched systems, IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics), 38 (2008), 1419–1422.

[35] S. Y. Yoon and Z. Lin, Truncated predictor feedback control for exponentially unstable linear systems with time-varying input delay, Systems & Control Letters, 62 (2013), 837–844.

[36] B. Zhou, Z. Lin and G.-R. Duan, Global and semi-global stabilization of linear systems with multiple delays and saturations in the input, SIAM Journal on Control and Optimization, 48 (2010), 5294–5332.

[37] B. Zhou, Z. Lin and G.-R. Duan, Truncated predictor feedback for linear systems with long time-varying input delays, Automatica, 48 (2012), 2387–2399.

[38] B. Zhou, Z. Lin and G. Duan, Stabilization of linear systems with input delay and saturation parametric lyapunov equation approach, International Journal of Robust and Nonlinear Control, 20 (2010), 1502–1519.

[39] Z. Zuo, Z. Lin and Z. Ding, Truncated predictor control of lipschitz nonlinear systems with time-varying input delay, IEEE Transactions on Automatic Control, 62 (2017), 5324–5330.

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