Stability Analysis of Variable Sampled-Data Control Systems with Control Inputs Missing

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Abstract: In this paper, we study the stability analysis problem for variable sampled-data control systems with control inputs missing. Sufficient conditions for exponential stability are developed for a class of switching signals with average dwell time. The sampling period is not required to be a constant, and the only assumption is that the sampling intervals are less than a given upper bound. By using the input delay approach, the variable sampled-data control system with control inputs missing is transformed into switched systems with varying-time delay consisting of two subsystems. A class of switching signals with average dwell time approach is identified to guarantee the exponentially stable. The state decay estimate is explicitly given. An example of satellite yaw control system is given to show the effectiveness of the proposed result.

Key Words: Control inputs missing, Exponential stability, Variable sampled-data, Switched systems, Average dwell time

1 Introduction

Sampled-data control theory has been studied extensively in the past decades because modern control systems usually employ digital technology for controller implementation. A great number of papers on this topic have been reported in the past few decades [1–6]. Two main approaches have been used to the sampled-data control problem. The first one is based on the lifting technique [7], and the other is based on the representation the system in the form of hybrid discrete/continuous models. The continuous-time systems with sampled-data control also can be modeled as continuous-time systems with delayed control inputs, which can be applied to systems with variable sampled-data [3,8].

One the other hand, the control inputs missing is a common phenomenon in engineering control design [9]. Here, control inputs missing means that the control input is zero, that is, the control system runs in the open loop. It is obvious that the sampled-data control system is not stability if the total time of the control inputs missing is too long. [10] investigated the stabilization problem for the sampled-data control with control inputs missing. The sampling intervals are considered to be constant in [10]. However, the sampler may contain uncertainties or the mathematical model is not ideally consistent with the sampling equipment, the uncertain sampling may happen [11]. Searching stability conditions for variable sampled-data control with missing control inputs is obviously more preferable and challenging, which partly motivates our present work.

In this work, based on the input delay approach, the variable sampled-data control with control inputs missing will be transformed into a switched delay system consisted of two subsystems: one is closed-loop system, the other is open-loop system. The switching signal between the two subsystems is driven by whether there exists control inputs missing. Switching instants must be the sampling instants. We know that the switched systems with time delay have drawn considerable attention (see, for example, [12–14]). Average dwell time technique has been proved to be an effective tool to study the stability of switched system with time delay [12,13]. However, [12] and [13] assumed that the delay is differentiable for all time and the delay derivative is smaller then one. Therefore, when the delay derivative equals to one, [12] and [13] are not applicable. On the other hand, in the method of average dwell time, a “μ” condition is often imposed where a maximal global constant ratio is required among the functions, i.e. $V_q \leq \mu V_q$ for $\mu \geq 1$, $p$, $q$ are the numbers of modes [15]. However, $\mu$ is not always easy to find [16]. In [10], two Lyapunov functionals were introduced to estimate the exponential increase for closed-loop system and decrease for open-loop system, respectively. Therefore, [10] has the same difficulty to satisfy this “μ” condition. In fact, we do not make $V_q \leq \mu V_q$ for $\mu \geq 1$ hold for all time, and we only make it hold at the switching times.

In this paper, by using a Lyapunov functional, sufficient conditions for the existence of feedback controller are obtained and use this Lyapunov functional to estimate the decrease for the closed-loop (stable) subsystem. Such a Lyapunov functional is continuous in time and becomes a quadratic function at the sampling times. As opposed to [10], which use a Lyapunov functional and need to solve some matrix inequalities to construct such a functional, we introduce another quadratic function to estimate the increase for the open-loop (unstable) subsystem without solving any matrix inequalities. For the two designed quadratic functions, it is easy to compute such a “μ” at the switching times.

This paper studies the stability analysis of variable sampled-data system with control inputs missing. Unlike [10], which deals with a constant sampling interval, the sampling intervals are variable and bounded by a known constant.
By using the input delay method, the system considered in this paper is described by a switched variable sampled-data model, and is then transformed into a continuous-time switched linear system with varying-time delay consisted by two subsystems, one stable and the other unstable. Based on the average dwell time method, sufficient conditions are obtained to guarantee the exponentially stable of the sampled-data control systems. One of the advantages of the proposed method is that the obtained lower bounded of the average dwell time is less than the one obtained in [10]. One example of satellite yaw control system is given to illustrates the effectiveness of the proposed method.

2 Formulation and Preliminaries

Consider the linear system:
\[ \dot{x}(t) = Ax(t) + Bu(t), \]  
(1)

where \( x(t) \in \mathbb{R}^n \) is the state vector, \( u(t) \in \mathbb{R}^n_u \) is the control input. \( A \) and \( B \) are constant matrices with appropriate dimensions. For sampled-data stabilization, only discrete measurements of \( x(t) \) can be used for control purpose, that is, we use the following control signal:
\[ u(t) = u(t_k) = Kx(t_k), t \in [t_k, t_{k+1}), k = 0, 1, 2, \cdots, \]  
(2)

where \( t_k \) denotes the sampling instant, and \( k \to \infty t_k = \infty \).

Under the controller (2), the closed-loop system (1) is given by
\[ \dot{x}(t) = Ax(t) + BKx(t_k), t \in [t_k, t_{k+1}), \]  
\[ k = 0, 1, 2, \cdots. \]  
(3)

Since the sampler may contain uncertainties, we make the following assumption.

Assumption 1. It is assumed that the distance between any two sampling instant is bounded by \( h(h > 0) \), that is,
\[ t_{k+1} - t_k \leq h, \forall k \geq 0. \]  
(4)

Remark 1. In the literature of sampled-data stabilization problem, the Assumption 1 can be found in [2, 11]. Assumption 1 implies that the sampling periods may be varying form sample to sample.

During any sampling interval \([t_k, t_{k+1}), k = 0, 1, 2, \cdots,\) we have \( u(t) = 0 \) when the control inputs are missed, and \( u(t) = u(t_k) \) otherwise. Similar to [10], we introduce an indicator \( \sigma(t) \in \{s, u\} \) which denotes the data missing status, where \( s \) and \( u \) are two symbols. We have \( \sigma(t) = u \) when data missing occurs, and \( \sigma(t) = s \) otherwise. With these notations, the sampled-data control system with missing control inputs is given by:
\[
\begin{align*}
S_s : \dot{x}(t) &= Ax(t) + BKx(t_k), &\sigma(t) &= s, \\
S_u : \dot{x}(t) &= Ax(t), &\sigma(t) &= u,
\end{align*}
\]  
(5)

It is seen from (5) that the sampled-data system with control inputs missing is essentially a switched system with a stable subsystem (closed-loop subsystem) and an unstable one (open-loop subsystem).

By an input delay approach in [3], we represent the sampled-data control as a delayed control:
\[ u(t) = u(t_k) = u(t - \tau(t)), \tau(t) = t - t_k, \]  
\[ t \in [t_k, t_{k+1}). \]  
(6)

Then, the system (5) can be transformed to a continuous-time switched system with time-varying delay:
\[ \dot{x}(t) = Ax(t) + B\sigma(t)x(t - \tau(t)), \quad t \in [t_k, t_{k+1}), \]  
\[ x(t) = \varphi(t) = \varphi(t_0), \quad t \in [t_0 - h, t_0), \]  
(7)

where \( k = 0, 1, 2, \cdots, \) \( x(t) = \varphi(t) = x(t_0) \) for \( t \in [t_0 - h, t_0) \) is the initial condition, \( \sigma(t) \) denotes the switching signal, and \( B_0 = BK, B_u = 0, \tau(t) = 1 \) for \( t \neq t_k \).

Remark 2. When \( t_{k+1} - t_k \equiv h' \leq h, \forall k \geq 0, \) the system (7) under consideration becomes the one in [10]. Unlike in [10] where the sampling period is a constant, we will study the case of the variable sampled period.

Now, we have transformed the sampled-data closed-loop system (5) with control inputs missing into a switched system (7) with time-varying delay consisting of two subsystems. In the following, we will investigate how to design a stabilizing sampled-data controller and indentify a class of switching signals to guarantee the system (7) is exponentially stable. Next, we introduce the following definition.

Definition 1. The equilibrium \( x^* = 0 \) of the system (7) is said to be exponentially stable under \( \sigma(t) \) if the solution of the system (7) satisfies
\[ \|x(t)\| \leq \Gamma \|x_{t_0}\| \exp \left(-\lambda(t - t_0)\right), \forall t \geq t_0, \]  
(8)

for constants \( \Gamma \geq 1 \) and \( \lambda > 0 \), where \( \|\cdot\| \) denotes the Euclidean norm, and \( \|x\| = \sup_{-h \leq \theta \leq 0} \|x(t + \theta)\|, \|x\|_{L_1} = \sup_{-h \leq \theta \leq 0} \{\|x(t + \theta)\|, \|\dot{x}(t + \theta)\|\} \).

Definition 2. For any \( \tau_1 > \tau_2 \geq 0, \) let \( N_\sigma(\tau_1, \tau_2) \) denote the number of switching \( \sigma(t) \) of over \([\tau_1, \tau_2]\). If \( N_\sigma(\tau_1, \tau_2) \leq N_0 + (\tau_2 - \tau_1)/T_a \) holds for \( T_a > 0 \) and \( N_0 \geq 0, \) then \( T_a \) is called the average dwell time and \( N_0 \) the chatter bound.

For simplicity, but without loss of generality, we choose \( N_0 = 0 \).

Notations. \( P > 0 \) denotes that the matrix \( P \) is positive definite. \( \lambda_{\min}(\cdot) \) and \( \lambda_{\max}(\cdot) \) denote the minimum and the minimal eigenvalues of matrix \( \cdot \), respectively.

3 Main Result

In this section, we will present sufficient conditions for existing a sample-data controller and then identify a class of switching signals under which the sampled-data control system with control inputs missing is globally exponentially stable.

For the system (7) when \( t \in [t_k, t_{k+1}), \sigma(t) = s, \) we
consider the following Lyapunov functional:

\[ V_{\text{var}}(t, x_1, x_2) = V_s(t) = \begin{cases} x^T(t)P_{s_1}x(t) + \int_{t-k}^{t} e^{2\alpha(s-t)}x^T(s)Ux^T(s)ds \\
+ (t_{k-1} - t) \xi^T(t) \begin{bmatrix} X + X^T \choose * \end{bmatrix} \xi(t), \\
& t \in [t_k, t_{k+1}), 
\end{cases} \tag{9} \]

where \( \xi^T(t) = (x(t), x(t_k)) \).

**Lemma 1.** [2] For given \( \alpha > 0 \), suppose Assumption 1 holds and there exist matrices \( P > 0, U > 0, X, X_1, P_2, P_3, T, Y_1, Y_2, K \) such that the following matrices inequalities are feasible:

\[ \Xi(h) = \begin{bmatrix} P + h \frac{X + X^T}{2} & hX_1 - hX \\
* & hX_1 - hX_1^T + h \frac{X + X^T}{2} \end{bmatrix} > 0, \tag{10} \]

\[ \Psi_0(h) = \begin{bmatrix} \Phi_{11} - X_\alpha^* & \Phi_{12} + h \frac{X + X^T}{2} & \Phi_{13} + X_{1|0}(t) = 0 \\
* & \Phi_{22} + hU & \Phi_{23} - h(X - X_1) \\
* & * & \Phi_{33} - X_{2|0}(t) = 0 \end{bmatrix} < 0, \tag{11} \]

\[ \Psi_1(h) = \begin{bmatrix} \Phi_{11} - \frac{X + X^T}{2} & \Phi_{12} & \Phi_{13} - X - X_1 \\
* & \Phi_{22} & \Phi_{23} \\
* & * & \Phi_{33} - X_{2|0}(t) = h \end{bmatrix} < 0, \tag{12} \]

where \( \Phi_{11} = A^T P_2 + P_2^T A + 2\alpha X P - Y_1 - Y_1^T, \Phi_{12} = P - P_2^T + A^T P_3 - Y_2, \Phi_{13} = Y_1^T + P_2^T A_1 - T, \Phi_{22} = -P_3 - P_3^T, \Phi_{23} = Y_2^T + P_3^T A_1, \Phi_{33} = T + TT^T, X_\alpha = \left[ 1 - 2\alpha(h - \tau(t)) \right] \frac{X + X^T}{2}, X_\alpha^* = X_{1(t)=0} X_{1(t)=0} = (h - \tau(t)) \frac{X + X^T}{2}, X_{1(t)=0} = (h - \tau(t)) (X - X_1), X_{1|0} = \left[ 1 - 2\alpha(h - \tau(t)) \right] (X - X_1), X_{2|0} = \left[ 1 - 2\alpha(h - \tau(t)) \right] \frac{X + X^T}{2} - X_1, A_1 = BK. \]

Then, along the trajectory of system (7) without control inputs missing, we have

\[ V_s(t) \leq -2\alpha_s V_s(t), \sigma(t) = s, t \in [t_k, t_{k+1}). \tag{13} \]

**Remark 3.** It is easy to show that the last two terms of (9) vanish before \( t_k \) and after \( t_k \). In addition, \( \lim_{t \rightarrow t_k^+} V_s(t) = V_s(t_k) \), so \( V_s \) is continuous at the sample times.

Without loss of generality, we assume that \( A \) is not Hurwitz in this paper.

Define

\[ V_u(x(t)) = x^T(t)P_u(x(t)), P_u > 0. \tag{14} \]

**Proposition 1.** There exists a constant \( \alpha_u < 0 \), such that

\[ V_u(x(t)) \leq -\alpha_u V_u(x(t)), \sigma(t) = u, t \in [t_k, t_{k+1}). \tag{15} \]

**Proof.** If \( \sigma(t) = u \) when \( t \in [t_k, t_{k+1}) \), then,

\[ \dot{V}_u(x(t)) = x^T(t) (A^T P_u + P_u A) x(t) \]
\[ = x^T(t) Q x(t), t \in [t_k, t_{k+1}), \tag{16} \]

that is, \( \dot{V}_u(x(t)) \leq -\alpha_u V_u(x(t)), t \in [t_k, t_{k+1}). \)

The proof is completed.

**Remark 4.** The Proposition 1 gives the estimation on the exponential increase of \( V_u \). In fact, a quadratic function \( V_u \) defined in (14) is reasonable for linear systems without time-delay. \( V_u \) is more simple than the one in [10] which adds an additional double integral term. The construction of \( V_u \) does not solve any matrix inequalities.

In this paper, we will use the average dwell time method to handle the problem proposed.

It is easy to show that there exists a constant \( \mu \geq 1 \), such that \( P \leq \mu P_u \) and \( P_u \leq \mu P \). For example, one can choose

\[ \mu = \max \left\{ \frac{\lambda_{\text{max}}(P)}{\lambda_{\text{min}}(P_u)} \right\} \]

Similar to [10], we let \( t_s, t_0 \) be the total activation time of subsystem \( s \) and subsystem \( u \) over the interval \([t_0, t]\). Define

\[ \Delta_u = \frac{t_s}{t_t} \text{ and } \Delta_u = \frac{t_0}{t_{t_0}}. \]

**Theorem 1.** For given \( \alpha_s > 0 \), suppose the system (7) satisfying Assumption 1, if matrices inequalities (10), (11) and (12) are feasible for \( K \in \mathbb{R}^{1 \times n} \) and \( n \times n \)-matrices \( P > 0, U > 0, X, X_1, P_2, P_3, T, Y_1, Y_2 \), then there exists a constant \( \mu \geq 1 \), such that \( P \leq \mu P_u \) and \( P_u \leq \mu P \), where \( P_u > 0 \) defined in (14). In addition, if

\[ \Delta_u \leq \Delta^*_u = \left( \frac{-\ln \mu}{T^*} + \alpha_s \right) / (\alpha_s - \alpha_u), \tag{18} \]

where \( \alpha_u \) defined in Proposition 1, then the system (7) is globally exponentially stable for every switching signal \( \sigma \) with average dwell time

\[ T^*_u > T^* = \frac{-\ln \mu}{\alpha_s}. \tag{19} \]

**Proof.** Similar to [10], we denote \( T_1^+, \ldots, T_j^+ \) the switching instants of \( \sigma(t) \) on the interval \([t_0, t]\) where \( t_0 < T_1^+ < \cdots < T_j^+ < t, j \geq 1 \). \( T_j^+ \) is the time instant that is immediately after \( T_j \), \( i = 1, 2, \ldots, j \), where \( T_i \) is some sampling instant and belongs to \( \{t_1, t_2, \ldots\} \).

Since the switching instance is the sampling instant and the state of the system does not jump at the switching instants,
we have
\[ V_{\sigma(t)}(t) \leq e^{-\alpha t}(T^+_{t_j})(T^+_{t_j}) \]
\[ \leq \mu e^{-\alpha t}(T^-_{t_j})(T^+_{t_j}) \leq \cdots \]
\[ \leq \mu N_s(t_0)e^{-\alpha t}(T^+_{t_j})(T^+_{t_j}) \leq \cdots \]
\[ \times e^{-\alpha t}(T^-_{t_j})(T^+_{t_j}) \]
\[ = \mu N_s(t_0)e^{-\alpha t}V_{\sigma(t_0)}(t^+_{t_0}) \]
\[ = e^{N_s(t_0)\mu}e^{-\alpha t}V_{\sigma(t_0)}(t^+_{t_0}) \]
\[ \leq e^{\frac{\alpha}{\mu}}(t_0)e^{-\alpha t}e^{-\alpha t}V_{\sigma(t_0)}(t^+_{t_0}) \]
\[ e^{-\lambda \alpha t} - (1 - e^{-\alpha t})V_{\sigma(t_0)}(t^+_{t_0}) \]
\[ = e^{-\lambda \alpha t}V_{\sigma(t_0)}(t^+_{t_0}) \] (20)

with \( \lambda = 0.5 \frac{\ln \mu}{\Delta u} + \alpha_s - (\alpha_s - \alpha_u) \Delta u \), that is,
\[ V_{\sigma(t)}(t) \leq e^{-\lambda \alpha t}V_{\sigma(t_0)}(t^+_{t_0}). \] (21)

Then, we further obtain from (21) that
\[ \min \{ \lambda_{\min}(P), \lambda_{\min}(P_u) \} \| x(t) \|^2 \leq V_{\sigma(t)}(t) \leq e^{-\lambda \alpha t} \max \{ \lambda_{\max}(P), \lambda_{\max}(P_u) \} \| x(t_0) \|^2, \] (22)

which yields
\[ \| x(t) \| \leq e^{-\lambda \alpha t} \| x(t_0) \|, \] (23)

where \( \Gamma = \sqrt{\max \{ \lambda_{\max}(P), \lambda_{\max}(P_u) \} / \min \{ \lambda_{\min}(P), \lambda_{\min}(P_u) \}} \).

Equation (18) guarantees \( \lambda = \frac{1}{2} \left( -\frac{\ln \mu}{\Delta u} + \alpha_s - (\alpha_s - \alpha_u) \Delta u \right) > 0 \). So, the system (7) is exponentially stable.

The proof is completed.

**Remark 5.** Theorem 1 contains the constant sampling intervals, i.e., \( t_{k+1} - t_k \equiv h \leq h, k = 0, 1, 2, \cdots \), as a special case. For the constant sampling intervals and fixed \( \alpha_s, \mu \), the lower bound of the average time is
\[ T^* = \frac{\ln \mu}{\alpha_s}, \]
which is less than the one obtained in [10] where
\[ T^* = \frac{\ln \mu + 0.5h (\alpha_s - \alpha_u)}{\alpha_s} \]
with \( \alpha_s - \alpha_u > 0 \).

**Remark 6.** To ensure \( \lambda > 0 \), we need to impose the condition (18). Similar condition with (18) can be found in [10].

For given \( \alpha_s, \alpha_u, \mu, T_u \), the exponential decay rate is a linear monotonic decreasing function in \( \Delta u \) and
\[ \lambda(\Delta u) = -\frac{1}{2} (\alpha_s - \alpha_u) \Delta u - \frac{1}{2} \left( -\frac{\ln \mu}{T_u} + \alpha_s \right), \] (24)

which implies that for a fixed \( \Delta u \), the stability performance \( \lambda \) obtained in Theorem 1 is better than the one in [9] where
\[ \lambda(\Delta u) = -\frac{1}{2} (\alpha_s - \alpha_u) \Delta u - \frac{1}{2} \ln \mu + \alpha_s - \frac{1}{2} (\alpha_s - \alpha_u) h \]
since \( \frac{1}{2} (\alpha_s - \alpha_u) h > 0 \).

**4 Example**

In this section, we will apply the proposed method to study a satellite yaw angles control system represented by the following dynamic equations:
\[ J_1 \ddot{\theta}_1(t) + f(\dot{\theta}_1(t) - \dot{\theta}_2(t)) + k(\theta_1(t) - \theta_2(t)) = u(t), \]
\[ J_2 \ddot{\theta}_2(t) + f(\dot{\theta}_1(t) - \dot{\theta}_2(t)) + k(\theta_1(t) - \theta_2(t)) = 0, \] (25)
The physical meaning of the parameters of this system can be found in [17]. A state-space representation of the above equation is given by
\[ M \begin{bmatrix} \dot{\theta}_1(t) \\ \dot{\theta}_2(t) \end{bmatrix} = F \begin{bmatrix} \theta_1(t) \\ \theta_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u, \] (26)

where \( M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & J_1 & 0 \\ 0 & 0 & 0 & J_2 \end{bmatrix} \), \( F = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & -k & f \\ 0 & 0 & 0 & 1 \\ -k & f & -f & 0 \end{bmatrix} \).

Here we choose \( J_1 = J_2 = 1, k = 0.3 \) and \( f = 0.004 \). Then we have
\[ A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -0.3 & 0.3 & -0.004 & 0.004 \\ 0.3 & -0.3 & 0.004 & -0.004 \end{bmatrix} \], \( B = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}^T \).

The eigenvalues of \( A \) are \(-0.004 + 0.7746i, -0.004 - 0.7746i, 0, 0\). It is easy to show that the system above is not stable without control input.

Let \( \alpha_s = 0.16 \) and \( h = 1 \). By using Lemma 1, we obtain the following matrices: \( K = [-1.6, -0.3, -2.7, -5.3] \),
\[ P = \begin{bmatrix} 21.0540 & 0 & 0 & 0 \\ 0 & 21.0540 & 0 & 0 \\ 0 & 0 & 21.0540 & 0 \\ 0 & 0 & 0 & 21.0540 \end{bmatrix}, \]
\[ U = \begin{bmatrix} 20.2049 & 0 & 0 & 0 \\ 0 & 20.2049 & 0 & 0 \\ 0 & 0 & 20.2049 & 0 \\ 0 & 0 & 0 & 20.2049 \end{bmatrix}. \]
Fig. 1: State responses of the system (26) with variable sampling.

Fig. 2: Control input of the system (26) with variable sampling.

Fig. 3: State responses of the system (26) with constant sampling.

Fig. 4: Control input of the system (26) with constant sampling.

If we set $P_u = P$, then $\lambda(Q) = \pm 21.0504, -8.5903, 8.2535$ and $\lambda(P_u) = 21.0504$. With the help of Proposition 1, we obtain $\alpha_u = -1$. By (19), we know that $T_u > T^* = \frac{\ln \mu}{\alpha_u} = 0$. From (18), we know that $\Delta_u^* = \frac{-\ln \mu}{\alpha_u - \alpha_s} = 0.1379$. We choose $\Delta_u = 12.5% < \Delta_u^*$, then we have $\lambda(\Delta_u) = 0.0075$.

5 Concluding Remarks

We have investigated the stability analysis problem of variable sampled-data control with control inputs missing. The sampling intervals are not required to be a fixed constant, and the sampling intervals, which are less than a given bound, are variable. This problem was solved by utilizing an input-delay approach, which represented the variable sampled-data control system with control inputs missing as a switched system with varying-time delay consisting of two subsystems. A class of switching signals with average dwell time is identified to guarantee that the system under consideration is exponentially stable. An illustrative example has been used to show the effectiveness of the main result.

References


