Event-triggered sampled-data synchronization of complex networks with time-varying coupling delays

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Abstract

This paper investigates the event-triggered sampled-data synchronization problem of complex networks with time-varying coupling delays. The sampled-data controller is designed with event-triggered mechanisms. Some results in terms of a linear matrix inequality are obtained to guarantee the asymptotical synchronization of complex networks with time-varying coupling delays. Lastly, we test the effectiveness of the proposed method via some numerical examples.

Keywords: Complex networks; Event-triggered; Sampled-data; Synchronization

1 Introduction

Recently, many synchronization schemes for complex networks have been proposed. Some synchronization strategies can achieve good performance by various methods [1–15]. In this paper, the main central point is constricted in the field of sampled-data control due to the development of digital control techniques that has occurred in two decades. Generally, there exist several methods or techniques concerning with digital control. For example, discretization is the most direct approach applied to digital control. However, owing to the complicated dynamics of chaotic Lur'e systems, the exact discrete model is with difficultly obtained. In order to improve the inter-sampling performance, sampled-data control has been often utilized to build hybrid system models via a zero-order hold (ZOH) [7–13]. For example, the sampled-data fuzzy controller was designed for chaotic synchronization in [7] and sampled-data synchronization of chaotic Lur'e systems with time delays was also studied in [13]. However, these schemes have been generally demanded with a fixed sampling period and the actual sampling rate maybe is very high. Aim to solve the above problem, the event-triggered sampled-data controller can be designed to apply for the synchronization of chaotic Lur'e systems. Nowadays, some results for event-triggered control are enumerated, such as [16–18]. Following these novel ideas, the event-triggered communication scheme is considered and the sufficient condition in terms of linear matrix inequality (LMI) is derived to guarantee the asymptotical synchronization of chaotic Lur'e systems. The main contributions of this paper can be described

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as: (1) event-triggered nonuniform sampling is considered in complex networks with time-varying coupling delays; (2) the nonlinear part of the node system is also handled.

2 Problem formulation

Consider the following complex networks with time-varying coupling delays consisting of N nodes via an event-triggered control approach:

$$
\dot{x}_i(t) = Ax_i(t) + Bf\big(x_i(t)\big) + c \sum_{j=1}^{N} g_{ij}\Gamma x_j\big(t - \tau(t)\big)
$$
$$
+ u_i(t_{i_k}), \quad t \in [t_{i_k}, t_{i_{k+1}}), \tag{1}
$$

where $i = 1, 2, \ldots, N$, N is the number of nodes, $k = 0, 1, \ldots, \infty$, $x_i(t) \in \mathbb{R}^n$ denotes the state vector associated with the ith node, t_{i_k} denotes the event-triggered instant and it is determined by the transmission error and the state error, $u_i(t_{i_k}) \in \mathbb{R}^n$ denotes the designed control law where the transmitted data packets are utilized along with the event-triggered control happening, $\tau(t)$ denotes the time-varying delay and satisfies the condition $\dot{\tau}(t) < \nu \le 1$, $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$ are known constant matrices, $f : \mathbb{R}^n \to \mathbb{R}^m$ is a continuous vector-valued function, c is a constant coupling strength, $\Gamma \in \mathbb{R}^{n \times n}$ denotes the inner coupling matrix, $G = (g_{ij})_{N \times N}$ is the coupling configuration matrix: if nodes i and j ($i \ne j$) are connected, then $g_{ij} > 0$, otherwise $g_{ij} = 0$, the diagonal elements of matrix G are defined by $g_{ii} = -\sum_{j=1,i\ne j}^{N} g_{ij}$, $i = 1, 2, \ldots, N$. t_k denotes the whole sampling instant and it is irregular. Moreover, the serial number of transmitted data packets, denoted as i_k, may be discontinuous for the existence of event-triggered mechanism where the transmitted data packets refer to the ones successfully arriving at the plant. $i_k \in \mathbb{N}$ denotes the serial number of the transmitted data packet such that $\{i_0, i_1, i_2, \ldots\} \subseteq \{0, 1, 2, 3, \ldots\}$.

Let $e_i(t) = x_i(t) - s(t)$ be the error vectors, where $s(t) \in \mathbb{R}^n$ is a solution of a target node satisfying $\dot{s}(t) = As(t) + Bf(s(t))$. The sampled-data synchronization feedback controller is designed as

$$
u_i(t_{i_k}) = K_i e_i(t_{i_k}), \quad t \in [t_{i_k}, t_{i_{k+1}}), \tag{2}
$$

where K_i is the feedback gain matrix with appropriate dimensions. Then, the error dynamics of (1) can be obtained as follows:

$$
\dot{e}_i(t) = Ae_i(t) + Bg\big(e_i(t)\big) + c \sum_{j=1}^{N} g_{ij}\Gamma e_j\big(t - \tau(t)\big)
$$
$$
+ K_i e_i(t_{i_k}), \quad t \in [t_{i_k}, t_{i_{k+1}}), \tag{3}
$$

where $i = 1, 2, \ldots, N$ and $g(e_i(t)) = f(x_i(t)) - f(s(t))$. It is clear that (3) can be rewritten in a vector-matrix form,

$$
\dot{e}(t) = A_N e(t) + B_N \bar{g}\big(e(t)\big) + c(G \otimes \Gamma)e\big(t - \tau(t)\big)
$$
$$
+ Ke(t_{i_k}), \quad t \in [t_{i_k}, t_{i_{k+1}}), \tag{4}
$$

where $e(t) = [e_1^T(t), \ldots, e_N^T(t)]^T$, $\bar{g}(e(t)) = [g^T(e_1(t)), \ldots, g^T(e_N(t))]^T$, $K = \text{diag}\{K_1, \ldots, K_N\}$, $A_N = I_N \otimes A$, $B_N = I_N \otimes B$.

The error between the current sampling instant and the latest transmission instant can be calculated as $\bar{e}(t_{i_k+l}) = e(t_{i_k+l}) - e(t_{i_k})$ where $l = 1, 2, \ldots, d$, $d = i_{k+1} - i_k$. The event-triggered condition can be provided as

$$\bar{e}^T(t)\Phi\bar{e}(t) \geq \delta e^T(t)\Phi e(t), \tag{5}$$

where $\delta > 0$ is a given scalar parameter, Φ is a positive-definite weighting matrix with appropriate dimensions. If the event-triggered condition is satisfied, then the transmitted signals will be sent. Otherwise the sampling signals will not be sent. $\Omega := [t_{i_k}, t_{i_k+l})$ can be described as $\Omega = \bigcup_{l=1}^{d} \Omega_l$ where $\Omega_l := [t_{i_k+l-1}, t_{i_k+l})$.

Assumption 1 There exists a constant $h > 0$ such that

$$t_{k+1} - t_k \leq h, \quad k = 0, 1, \ldots, \infty, \tag{6}$$

where h denotes the upper bound of the interval between two consecutive sampling instants.

Assumption 2 ([19]) There exists a diagonal matrix $\Lambda = \text{diag}\{\lambda_1, \ldots, \lambda_N\} > 0$ such that the nonlinear part of the node system satisfies the following condition in the domain of definition:

$$\bigl(f(x) - f(y)\bigr)^T \bigl(f(x) - f(y)\bigr) \leq (x - y)^T \Lambda (x - y). \tag{7}$$

Combining (4) and (5), the final error dynamics can be described as

$$\begin{aligned}
\dot{e}(t) = {} & A_N e(t) + B_N \bar{g}\bigl(e(t)\bigr) + c(G \otimes \Gamma)e\bigl(t - \tau(t)\bigr) \\
& + K\bigl(e\bigl(t - d(t)\bigr) - \bar{e}(t_{i_k+l})\bigr), \quad t \in \Omega_l,
\end{aligned} \tag{8}$$

where $d(t) = t - t_{i_k+l}$. It is explicit that $-h \leq d(t) < 0$ due to Ω_l and (6). The control objective is to design the controller gain matrix K such that the error dynamics (8) is asymptotically stable, i.e., $e(t) \to 0$ as $t \to \infty$.

3 Main results

In this section, the event-triggered sampled-data synchronization scheme will be given.

Theorem 1 *Given the scalars $h > 0$, $\delta > 0$, the error dynamics (8) is global asymptotically stable concerning with the event-triggered condition (5), if there exist matrices $P = P^T > 0$, $Q = Q^T > 0$, $R = R^T > 0$, $\Phi = \Phi^T > 0$, $\Lambda = \text{diag}\{\lambda_1, \ldots, \lambda_N\} > 0$, any matrices N_1, N_2, N_3, M_1, M_2, M_3 with appropriate dimensions, and the controller gain matrix K, such that the following condition holds*:

$$\begin{bmatrix} \Theta & hN \\ * & -hR \end{bmatrix} < 0, \tag{9}$$

where

$$\Theta = \begin{bmatrix} \Phi_{11} & \Phi_{12} & \Phi_{13} & \Phi_{14} & \Phi_{15} \\ * & \Phi_{22} & \Phi_{23} & \Phi_{24} & \Phi_{25} \\ * & * & \Phi_{33} & \Phi_{34} & \Phi_{35} \\ * & * & * & \Phi_{44} & 0 \\ * & * & * & * & \Phi_{55} \end{bmatrix}, \qquad N = \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ 0 \\ 0 \end{bmatrix},$$

$$\Phi_{11} = Q + N_1 + N_1^T + M_1 A_N + A_N^T M_1^T + M_1 B_N B_N^T M_1^T + 3\Lambda,$$

$$\Phi_{12} = P + N_2^T - M_1 + A_N^T M_2^T,$$

$$\Phi_{13} = -N_1 + N_3^T + M_1 K + A_N^T M_3^T,$$

$$\Phi_{14} = c M_1 (G \otimes \Gamma),$$

$$\Phi_{15} = -M_1 K,$$

$$\Phi_{22} = hR - M_2 - M_2^T + M_2 B_N B_N^T M_2^T,$$

$$\Phi_{23} = -N_2 + M_2 K - M_3^T,$$

$$\Phi_{24} = c M_2 (G \otimes \Gamma),$$

$$\Phi_{25} = -M_2 K,$$

$$\Phi_{33} = -N_3 - N_3^T + M_3 K + K^T M_3^T + M_3 B_N B_N^T M_3^T + \delta\Phi,$$

$$\Phi_{34} = c M_3 (G \otimes \Gamma),$$

$$\Phi_{35} = -M_3 K,$$

$$\Phi_{44} = -(1 - v)Q,$$

$$\Phi_{55} = -\Phi.$$

Proof Construct the following Lyapunov–Krasovskii functional:

$$V(t) = e^T(t)Pe(t) + \int_{t-\tau(t)}^{t} e^T(s)Qe(s)\,ds + \int_{-h}^{0}\int_{t-\theta}^{t} \dot{e}^T(s)R\dot{e}(s)\,ds\,d\theta$$

where $P = P^T > 0$, $Q = Q^T > 0$, and $R = R^T > 0$. Moreover, the following equations hold for any appropriate dimensional matrices N_j ($j = 1, 2, \ldots, 3$) and M_l ($l = 1, 2, 3$):

$$\left[e^T(t)N_1 + \dot{e}^T(t)N_2 + e^T\big(t - d(t)\big)N_3 \right]$$

$$\times \left[e(t) - e\big(t - d(t)\big) - \int_{t-d(t)}^{t} \dot{e}(s)\,ds \right] = 0, \tag{10}$$

$$\left[e^T(t)M_1 + \dot{e}^T(t)M_2 + e^T\big(t - d(t)\big)M_3 \right] \times \left[-\dot{e}(t) + A_N e(t) + B_N \bar{g}\big(e(t)\big) \right.$$

$$\left. + c(G \otimes \Gamma)e\big(t - \tau(t)\big) + Ke\big(t - d(t)\big) - K\bar{e}(t_{i_k+l}) \right] = 0. \tag{11}$$

Combining (10) and (11), the corresponding time derivative of $V(t)$ is given by

$$
\begin{aligned}
\dot{V}(t) \leq{} & 2\dot{e}^T(t)Pe(t) + e^T(t)Qe(t) - (1-\nu)e^T\big(t-\tau(t)\big)Qe\big(t-\tau(t)\big) \\
& + h\dot{e}^T(t)R\dot{e}(t) + \int_{t+h}^{t}\dot{e}^T(s)R\dot{e}(s)\,ds + 2\big[e^T(t)N_1 + \dot{e}^T(t)N_2 \\
& + e^T\big(t-d(t)\big)N_3\big] \times \left[e(t) - e\big(t-d(t)\big) - \int_{t-d(t)}^{t}\dot{e}(s)\,ds\right] \\
& + 2\big[e^T(t)M_1 + \dot{e}^T(t)M_2 + e^T\big(t-d(t)\big)M_3\big] \times \big[-\dot{e}(t) + A_N e(t) \\
& + B_N \bar{g}\big(e(t)\big) + c(G \otimes \Gamma)e\big(t-\tau(t)\big) + Ke\big(t-d(t)\big) - K\bar{e}(t_{i_k+l})\big] \\
& + \bar{e}^T(t_{i_k+l})\Phi\bar{e}(t_{i_k+l}) - \bar{e}^T(t_{i_k+l})\Phi\bar{e}(t_{i_k+l}).
\end{aligned}
$$

Utilizing Lemma 1 and Lemma 2 in [20], (5), and (7), the following result can be obtained:

$$
\dot{V}(t) \leq \varsigma^T(t)\big(\Theta + hNR^{-1}N^T\big)\varsigma(t)
$$

where $\varsigma(t) = [e^T(t)\dot{e}^T(t)e^T(t-d(t))e^T(t-\tau(t))\bar{e}^T(t_{i_k+l})]^T$, matrices Θ and N are defined in (9). It is explicit that, if $\Theta + hNR^{-1}N^T < 0$ holds, then $\dot{V}(t) < 0$ for any nonzero $\varsigma(t)$. Using the Schur complement [21], the result in Theorem 1 can be obtained, and the proof is completed. □

Note that the condition (9) in Theorem 1 is not a LMI. Thus, set $M_1 = J$, $M_2 = \epsilon_1 J$, $M_3 = \epsilon_2 J$ and $JK = V$. Utilizing the Schur complement, the following corollary is obtained.

Corollary 1 *Given the scalars $\epsilon_1 > 0$, $\epsilon_2 > 0$, $h > 0$, $\delta > 0$, the error dynamics (8) is global asymptotically stable concerning with the event-triggered condition (5), if there exist matrices $P = P^T > 0$, $Q = Q^T > 0$, $R = R^T > 0$, $\Phi = \Phi^T > 0$, $\Lambda = \mathrm{diag}\{\lambda_1,\ldots,\lambda_N\} > 0$, any matrices $N_1, N_2, N_3, J,$ and V with appropriate dimensions, such that the following condition holds:*

$$
\begin{bmatrix} \bar{\Theta} & h\bar{N} \\ * & -hR \end{bmatrix} < 0, \tag{12}
$$

where

$$
\bar{\Theta} = \begin{bmatrix}
\bar{\Phi}_{11} & \bar{\Phi}_{12} & \bar{\Phi}_{13} & \bar{\Phi}_{14} & \bar{\Phi}_{15} & \bar{\Phi}_{16} & 0 & 0 \\
* & \bar{\Phi}_{22} & \bar{\Phi}_{23} & \bar{\Phi}_{24} & \bar{\Phi}_{25} & 0 & \bar{\Phi}_{27} & 0 \\
* & * & \bar{\Phi}_{33} & \bar{\Phi}_{34} & \bar{\Phi}_{35} & 0 & 0 & \bar{\Phi}_{38} \\
* & * & * & \bar{\Phi}_{44} & 0 & 0 & 0 & 0 \\
* & * & * & * & \bar{\Phi}_{55} & 0 & 0 & 0 \\
* & * & * & * & * & \bar{\Phi}_{66} & 0 & 0 \\
* & * & * & * & * & * & \bar{\Phi}_{77} & 0 \\
* & * & * & * & * & * & * & \bar{\Phi}_{88}
\end{bmatrix}, \quad
\bar{N} = \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix},
$$

$$
\bar{\Phi}_{11} = Q + N_1 + N_1^T + JA_N + A_N^T J^T + 3\Lambda,
$$

$$
\bar{\Phi}_{12} = P + N_2^T - J + \epsilon_1 A_N^T J^T,
$$

$$
\bar{\Phi}_{13} = -N_1 + N_3^T + V + \epsilon_2 A_N^T J^T,
$$

$$\bar{\Phi}_{14} = cJ(G \otimes \Gamma),$$

$$\bar{\Phi}_{15} = -V,$$

$$\bar{\Phi}_{16} = JB_N,$$

$$\bar{\Phi}_{22} = hR - J - J^T,$$

$$\bar{\Phi}_{23} = -N_2 + \epsilon_1 V - \epsilon_2 J^T,$$

$$\bar{\Phi}_{24} = c\epsilon_1 J(G \otimes \Gamma),$$

$$\bar{\Phi}_{25} = -\epsilon_1 V,$$

$$\bar{\Phi}_{27} = \epsilon_1 JB_N,$$

$$\bar{\Phi}_{33} = -N_3 - N_3^T + \epsilon_2 V + \epsilon_2 V^T + \delta\Phi,$$

$$\bar{\Phi}_{34} = c\epsilon_2 J(G \otimes \Gamma),$$

$$\bar{\Phi}_{35} = -\epsilon_2 V,$$

$$\bar{\Phi}_{38} = \epsilon_2 JB_N,$$

$$\bar{\Phi}_{44} = -(1-v)Q,$$

$$\bar{\Phi}_{55} = -\Phi,$$

$$\bar{\Phi}_{66} = -I,$$

$$\bar{\Phi}_{77} = -I,$$

$$\bar{\Phi}_{88} = -I.$$

Moreover, the sampled-data controller gain is given by $K = J^{-1}V$.

4 Numerical examples

In this section, two numerical examples are given to demonstrate the effectiveness of the proposed event-triggered sampled-data synchronization scheme.

Example 1 ([22]) A complex network with five coupled identical nodes is described as follows:

$$\dot{x}_i(t) = Ax_i(t) + Bf\big(x_i(t)\big) + \sum_{j=1}^{5} g_{ij}x_j\big(t - \tau(t)\big) + u_i(t), \quad i = 1, 2, \ldots, 5,$$

where

$$A = \begin{bmatrix} -am_1 & a & 0 \\ 1 & -1 & 1 \\ 0 & -b & 0 \end{bmatrix}, \qquad B = \begin{bmatrix} -a(m_0 - m_1) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$G = 0.2 \times \begin{bmatrix} -3 & 1 & 1 & 0 & 1 \\ 1 & -4 & 1 & 1 & 1 \\ 1 & 1 & -3 & 1 & 0 \\ 0 & 1 & 1 & -3 & 1 \\ 1 & 1 & 0 & 1 & -3 \end{bmatrix},$$

$$f(t) = 0.5\big(\big|x_{ik}(t) + c\big| - \big|x_{ik}(t) - c\big|\big), \quad k = 1,\dots,3,$$

$$a = 9, \qquad b = 14.28, \qquad c = 1, \qquad m_0 = -1/7, \qquad m_1 = 2/7,$$

$$\tau(t) = 0.4 + 0.1\sin(t), \qquad v = 0.1.$$

Setting $\epsilon_1 = \epsilon_2 = 1$, and $\delta = 0.1$, the condition (12) in Corollary 1 is feasible and the following result is obtained:

$$h_{\max} = 0.18,$$

$$K = \mathrm{diag}\{K_1, K_2, K_3, K_4, K_5\},$$

where

$$K_1 = K_3 = K_4 = K_5 = \begin{bmatrix} -2.0710 & 4.5512 & 0.3642 \\ 0.4899 & -1.8005 & 0.6312 \\ -0.3439 & -9.3591 & -1.4639 \end{bmatrix},$$

$$K_2 = \begin{bmatrix} -2.1161 & 4.6243 & 0.3494 \\ 0.5075 & -1.8259 & 0.6373 \\ -0.3655 & -9.3363 & -1.4738 \end{bmatrix}.$$

Example 2 ([22]) Complex network with three coupled identical nodes is described as follows:

$$\dot{x}_i(t) = Ax_i(t) + Bf\big(x_i(t)\big) + \sum_{j=1}^{3} g_{ij}x_j\big(t - \tau(t)\big) + u_i(t), \quad i = 1, 2, \dots, 3,$$

where

$$A = \begin{bmatrix} -0.5 & 0.2 \\ 0 & 0.95 \end{bmatrix}, \qquad B = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \qquad G = 0.5 \times \begin{bmatrix} -1 & 0 & 1 \\ 0 & -1 & 1 \\ 1 & 1 & -2 \end{bmatrix},$$

$$f(t) = \begin{bmatrix} \tanh(0.2x_{i1}(t)) \\ \tanh(0.75x_{i2}(t)) \end{bmatrix}, \qquad \tau(t) = 0.2 + 0.05\sin(10t), \qquad v = 0.05.$$

Setting $\epsilon_1 = \epsilon_2 = 1$, and $\delta = 0.1$, the condition (12) in Corollary 1 is feasible and the following result is obtained:

$$h_{\max} = 0.18,$$

$$K = \mathrm{diag}\{K_1, K_2, K_3\},$$

where

$$K_1 = K_2 = \begin{bmatrix} -2.7786 & 0.0222 \\ -0.1421 & -2.9535 \end{bmatrix}, \qquad K_3 = \begin{bmatrix} -2.8814 & 0.0291 \\ -0.1212 & -2.9829 \end{bmatrix}.$$

Through the above two numerical examples, we can find that the event-triggered sampled-data synchronization is guaranteed for complex networks with time-varying coupling delays.

5 Conclusion

In the present work, we deal with the event-triggered sampled-data synchronization problem of complex networks with time-varying coupling delays. In future work, more performance requirements for the event-triggered sampled-data synchronization of complex networks will be considered in a uniform network topological structure.

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