A Hybrid Event Trigger Mechanism and Time-Delay Partitioning Are Applied to Event-Driven Control Systems

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This paper proposes an idea of using time-delay partitioning to construct a Lyapunov–Krasovskii functional (LKF) to analyse event-driven network control systems (NCSs) with the $H_\infty$ performance. Firstly, select a mixed event-driven mechanism, in which an adjustable absolute trigger mechanism is added to the trigger condition. Trigger term can be indicated to use a delay model. Secondly, a suitable LKF is created, which makes use of time-delay partitioning. Based on Wirtinger inequality and linear matrix inequalities (LMI), the close system with $H_\infty$ performance index level is global uniform ultimate bounded. Finally, a numerical simulation example proves the effectiveness of the proposed method.

1. Introduction

With the rapid development of computer and networked technologies, data transmission via communication networks has received considerable research attentions [1–10]. Due to the advantages of the NCSs such as data sharing, low cost, and easy maintenance, it has been widely used in the field of process control, electricity system, aircraft control systems, automobile controlling systems, etc. The traditional control system is based on time-driven, but for the NCSs with limited resources, if the control tasks are executed periodically based on fixed time points, this not only wastes limited computing and bandwidth resources but also may cause network-induced phenomena such as network congestion, data transmission delay, and data loss. As a non-uniform scheduling mechanism, event-driven can effectively solve the abovementioned problems, so it has become a hot research topic at present.

In event-driven control, only when the system reaches the trigger threshold set in advance can the control instruction be executed or the information be transmitted. Therefore, event-driven control can achieve similar or better control performance and reduce data transmission rate, thus saving the limited network bandwidth, computation, energy, and other resources in the system. As such, fruitful results based on different event-driven schemes are made in [11–20]. The triggering threshold has a great effect on the implementation of control task [11, 12]; however, because the threshold of the static triggering mechanism is fixed, it is difficult to adjust for external interference and environmental changes. In order to overcome the above drawbacks, a dynamic event-triggered scheme has been addressed in [13–15]. Besides that, a $H_\infty$ controller is designed in [21], in which Markov jump systems are studied based on event-triggered considering finite time. Rahnama et al. [22] consider the effects of network-induced time delays, signal quantization, and data loss and show L-2-stability and robustness for the control design. Gu et al. [23] consider an adaptive $H_\infty$ filter, which is based on event triggered to solve the problem of decentralize in NCSs. Furthermore, in [24], observer-based fuzzy controller is proposed to stabilize the NCSs under event-triggered mechanism in [25]; the stabilization problem for nonlinear NCSs with a two-terminal event-triggered mechanism is concerned. It is worth noting that the LKF method is mainly used in the above research, which will bring certain conservativeness to the conclusion due to the different treatment methods for cross items.
In order to reduce the conservativeness of the conclusion, the investigators bring forward two different research directions. One way is to choose a suitable LKF, and the other is to select a better scaling method in the process of dealing with the integral terms. Rich investigative achievements have been achieved by LKF picking [26–30]. In the early years, a simple LKF for fixed-delay systems was adopted. In order to make the LKF contain more system information, fixed time delay and variable delay are added to the system status in LKF [26]. Come up with the opinion of using time-delay partitioning to establish LKF [27]. More explore consequences have been generated in dealing with integral items. Use Jensen inequality to process integral items in event-driven NCSs [31]. Seuret and Gouaisbaut [32] put forward inequality to deal with the integral terms in the system integral terms to bring more system information. Study of NCSs stability, which can introduce additional items in event-driven NCSs [31]. Seuret and Gouaisbaut [32]

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Motivated by the above discussions, in this paper, we focus on the H∞ performance analysis of network control system based on event trigger mechanism. The main contributions of this paper are summarized as follows. (i) Using mixed trigger mechanism to reduce network burden, that is, an adjustable parameter is added on the basis of the dynamic trigger mechanism, so as to avoid Zeno phenomenon and long-term nonsampling phenomenon. (ii) The LKF is constructed with the idea of time-delay partitioning, and a new method is used to remove the coupling between the input matrix and the output matrix. On this basis, Wirtinger inequality is used to scale down and reduce the conservativeness of the conclusion.

1.1. Notation. In this paper, Y > 0 (Y < 0) denotes that the symmetric matrix Y is positive (or negative). ℝⁿ is defined as n-dimensional Euclidean space. ℝ⁺ is defined as a set of n × m real matrix, X₀ refers to the transpose of X, ∗ denotes a symmetric term of a symmetric matrix, and ∥ ∥ refers to the Euclidean norm. Followed by M + Mᵀ, which is defined as He(M). Iₙ refers to the n-dimensional unit matrix; 0 refers to the m × m dimension block matrix. The rest of the paper is adapted to the needs of the text of the adaptive dimension matrix.

2. Problem Formulation

Consider the following kind of linear time invariant system as follows:

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + B₁u(t) + C₁₁\omega(t), \\
\dot{z}(t) &= D₁₁x(t) + B₂u(t) + C₂\omega(t), \\
y(t) &= D₂x(t),
\end{align*}
\]

where x(t) ∈ ℝᵐ is the state vector, u(t) ∈ ℝⁿ is the control input, y(t) ∈ ℝ⁰ is the control output, z(t) ∈ ℝ⁰ is the control regulated output, ω(t) ∈ L₁[0, ∞) is the square integrable disturbance input, A, B₁, B₂, C₁, C₂, D₁, and D₂ are any matrices with adaptive dimensions. The event-triggered communication mechanism can be described by

\[
t_{k+1}h = t_kh + \min_l \{h_l \mid \{i(\nu)\} \Phi_r(i(\nu)) \geq \delta y^T(t_kh)\Phi y(t_kh) + \theta(t)\},
\]

where \( \theta(t) = \beta e^{-\alpha t}, e(i(\nu)) = y(i(\nu)) - y(t) \) is the error between the output at the current sampling time i(\nu)h = t_kh + lh \ (l ∈ \mathbb{N}) and the output at the latest triggered time t_kh; \( \Phi \) is a symmetric positive matrix; h is the time sampling period; and \( \delta \in [0, 0.5] \) and \( \beta \in [0, 0.5] \) are given scalar. If \( \delta = 0 \), the system trigger threshold is the absolute trigger mechanism. If \( \beta = 0 \), the system trigger threshold is the relative trigger mechanism. If \( \delta > 0 \) and \( \beta > 0 \), the system trigger threshold is the mixed trigger mechanism.

Divide \( \Omega \) into subsets \( \Omega_l = [i_lh + d_{l+1}h + h + d_{lk}], \) i.e., \( \Omega = \bigcup \Omega_l \), where \( i_lh = t_{lk} + lh, l = 0, 1, \ldots, t_k - 1 \); \( i_lh \) and \( t_lh \) represent the current sampling time and triggering time, respectively. For \( l = t_{lk} \) or \( l = t_k - 1 \), then \( d_{l+1}h = d_{lk+1}h \); otherwise, \( d_{l+1}h = d_{l+1}h \). Note that \( h_l ≤ d_l \), \( h_l = d_{lk} \), and \( h_m = (h_l + h_k)/2 \). \( h_l \) and \( h_k \) represent the lower and upper bounds of the time delay \( h_l < h_m < h_k \):

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + B₁KD₂x(t - d(t)) - B₁Ke(i(\nu)h) + C₁ω(t), \\
\dot{z}(t) &= D₁₁x(t) + B₂KD₂x(t - d(t)) - B₁Ke(i(\nu)h) + C₂\omega(t), \\
u(t) &= Kx(t_kh), \quad t ∈ \Omega,
\end{align*}
\]

where u(t) is the controller law and control gain K.

Lemma 1 (see [12]). Given matrices D, E(t), and F of appropriate dimensions with E(t) satisfying \( E^T(t) \Phi E(t) ≤ I \), for any \( \epsilon > 0 \), the following inequality holds:

\[
DE(t)F + F^TED^T(t)D ≤ \epsilon DD^T + \epsilon^{-1}F^TF.
\]

Lemma 2 (see [12]). The following two inequalities are equivalent:

(a) There exists a symmetric and positive-definite matrix \( P \) satisfying

\[
\begin{bmatrix}
-P & A^T \\
A & -P^{-1}
\end{bmatrix} < 0.
\]

(b) There exists a symmetric and positive-definite matrix \( P \) and matrix Y satisfying

\[
\begin{bmatrix}
-P & (YA)^T \\
YA \ He(-Y) & P
\end{bmatrix} < 0.
\]

Lemma 3 (see [12]). For a given matrix R > 0, the following inequality holds for all continuously differentiable function \( \omega \) in \([a, b] → ℝ^n\):
\[
\int_a^b \omega^T(u)R\omega(u)du \geq \frac{1}{b-a}\left((\omega(b) - \omega(a))^T R(\omega(b) - \omega(a))\right) + \frac{3}{b-a} \mathfrak{F}^T \mathcal{R} \mathfrak{F},
\]

where \( \mathfrak{F} = \omega(b) + \omega(a) - 2/b - a \int_a^b \omega(u) \, du \).

3. Main Results

Definition 1 (see [33]). The state \( x(t) \) of the continuous-time system is GUUB, if for every \( x(0) \in \mathbb{R}^n \), there exists a positive constant \( \varepsilon \) and a time \( T \) satisfying \( x(t) \in \{ x : \|x\| \leq \varepsilon \} \), \( \forall t \geq t \). Moreover, the continuous-time system is ultimately bounded or stable if its state \( x(t) \) is GUUB.

The objective of this section is to explore system (3) meeting the following requirements:

(i) System (3) is globally uniformly ultimately bounded (GUUB) stability and eventually exponentially converges to the bounded region by LMI.

(ii) System (3) guarantees, under zero-initial conditions, \( \|z(t)\| < \gamma \|\omega(t)\| \) for all nonzero \( \omega \in L_2[0, \infty) \) and a given proper positive constant scalar \( \gamma \).

Theorem 1. Consider the closed-loop system (3) and parameters driving mechanism (2) with \( \delta, \beta, h_1 > 0, h_2 > 0, h_{m0} > 0 \). Given a scalar \( \gamma > 0 \), the close system (2) meets Hoo application if there exist matrices \( P > 0, H_1 > 0, H_2 > 0, H_3 > 0, \Phi > 0, R_1 > 0, R_2 > 0, R_3 > 0, J \) and \( U_i (i = 1, 2, 3, 4) \), matrices \( Z \) and \( S \), with appropriate dimensions such that

\[
\begin{bmatrix}
\Gamma_{11} + J & \Gamma_{12} & 0 \\
* & \Gamma_{22} & \Gamma_{23} & 0 \\
* & * & He(-B_1^TB_1Z) & \Gamma_{34}
\end{bmatrix} < 0,
\]

where

\[
\begin{bmatrix}
W_{11} & h_1(R_1A)^T a_1(R_1A)^T & 0 & \cdots & \cdots & 0 \\
* & -R_1 & 0 & \cdots & \cdots & 0 \\
* & * & -R_2 & \cdots & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\
* & * & * & \cdots & -12R_1 & 0 \\
* & * & * & \cdots & -12R_2 & 0 \\
* & * & * & \cdots & \cdots & -12R_3 \\
\end{bmatrix},
\]

\[
\begin{bmatrix}
-b_1S & PC_1 & B_1SD_1 -2R_1 & 0 & 0 \\
-h_1b_1S & h_1b_1C_1 & h_1b_1SD_1 & 0 & 0 \\
-a_1b_1S & a_1b_1C_1 & a_1b_1SD_1 & 0 & 0 \\
-a_1b_1S & a_1b_1C_1 & a_1b_1SD_1 & 0 & 0 \\
-b_1S & C_1 & B_1SD_1 & 0 & 0 \\
0 & 0 & 0 & 6b_1^2 & 0 \\
0 & 0 & 0 & 0 & 6b_1^2 \\
0 & 0 & 0 & 0 & 0 \\
\end{bmatrix},
\]

\[
\begin{bmatrix}
(\beta - 1)\Phi & 0 & -\Phi D_2 & 0 & 0 \\
* & -\gamma \Phi & 0 & 0 & 0 \\
* & * & W_{12} & -F_{26} & 0 \\
* & * & * & W_{26} & -F_{36} \\
* & * & * & * & W_{36} \\
\end{bmatrix},
\]

\[
\begin{bmatrix}
-(b_1^2R_1S)^T & 0 & \cdots & \cdots & 0 \\
(b_1^2R_1SD_1)^T & 0 & \cdots & \cdots & 0 \\
0 & 0 & \cdots & \cdots & 0 \\
0 & 0 & \cdots & \cdots & 0 \\
0 & 0 & \cdots & \cdots & 0 \\
\end{bmatrix},
\]
\[
\Gamma_{34} = \begin{bmatrix}
(PB_1 - B_1 Z)^T & h_1 (R_1 B_1 - B_1 Z)^T & a_2 (R_2 B_1 - B_2 Z)^T & a_3 (R_3 B_1 - B_3 Z)^T & (B_2 - B_3 Z)^T \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix},
\]
\[
\eta^T(t) = \begin{bmatrix} x^T(t) & x^T(t - d(t)) & x^T(t - h_1) & x^T(t - h_m) & x^T(t - h_2) \end{bmatrix} \begin{bmatrix} Q_1 & Q_2 & Q_3 & Q_4 & e^T(i \omega) \end{bmatrix} \omega^T(t),
\]
\[
Q_1 = \frac{1}{h_1} \int_{t-h_1}^t x^T(s) \, ds,
\]
\[
Q_2 = \frac{1}{h_1 - d(t)} \int_{t-d(t)}^{t-h_1} x^T(s) \, ds,
\]
\[
Q_3 = \frac{1}{h_m - d(t)} \int_{t-d(t)}^{t-h_m} x^T(s) \, ds,
\]
\[
Q_4 = \frac{1}{h_2 - h_m} \int_{t-h_m}^{t-h_2} x^T(s) \, ds,
\]
\[
W_{11} = H_1 + H_2 + H_3 + \text{He}(PA) - 4R_1,
\]
\[
W_{22} = 6D_1^2 VD_2 - 8R_2 - \text{He}(-U_1 - U_2 + U_3 + U_4),
\]
\[
W_{33} = -H_1 - 4R_1 - 4R_2,
\]
\[
W_{44} = -H_2 - 4R_2,
\]
\[
W_{55} = -H_3 - 4R_3,
\]
\[
F_{23} = 2R_2 + U_1^T + U_2^T + U_3^T + U_4^T,
\]
\[
F_{24} = 2R_2 + U_1 - U_2 - U_3 + U_4,
\]
\[
F_{27} = -6R_2 - 2(U_3^T + U_4^T),
\]
\[
F_{34} = -U_1 + U_2 - U_3 + U_4,
\]
\[
F_{38} = -2(U_2 + U_4),
\]
\[
F_{47} = 2(U_3 - U_4^T).
\]

Then, the closed-loop system (3) based on the mixed event trigger mechanism (2) achieves GUUB. When \( t \to \infty \), the system state \( \xi(t) \) exponentially converges to the bounded area:

\[
\mathcal{F} = \begin{cases} 
\mathcal{F}_0 & \text{if } \|x(t)\| \leq \frac{\beta}{\sqrt{\lambda_{\text{min}}(P)}}, \quad \beta > 0, \quad \alpha = 0, \\
0 & \text{otherwise.}
\end{cases}
\]

**Proof.** Using the delay partitioning method to construct a suitable LKF for the paper,

\[
V(t) = x^T(t)Px(t) + \int_{t-h_1}^t x^T(s)H_1 x(s) \, ds + \int_{t-h_m}^t x^T(s)H_2 x(s) \, ds + \int_{t-h_2}^t x^T(s)H_3 x(s) \, ds
\]
\[
+ h_1 \int_{-h_1}^0 \int_{t+s}^t \dot{x}^T(v)R_1 \dot{x}(v) \, dv \, ds + a_2 \int_{-h_1}^{h_1} \int_{t+s}^t \dot{x}^T(v)R_2 \dot{x}(v) \, dv \, ds
\]
\[
+ a_3 \int_{-h_2}^{h_2} \int_{t+s}^t \dot{x}^T(v)R_3 \dot{x}(v) \, dv \, ds,
\]

where \( a_2 = d(t) - h_1 \) and \( a_3 = h_m - d(t) \). Taking the time derivative of (12) yields
\[
\dot{V}(t) = 2x^T(t)Px(t) + x^T(t)(H_1 + H_2 + H_3)\dot{x}(t) - x^T(t - h_1)H_1x(t - h_1) - x^T(t - h_m)H_2x(t - h_m),
\]
\[
- x^T(t - h_1)H_3x(t - h_1) + h_1^2\dot{x}^T(t)R_1\dot{x}(t) + a_2^2\dot{x}^T(t)R_2\dot{x}(t) + a_3^2\dot{x}^T(t)R_3\dot{x}(t),
\]
\[
- h_1 \int_{t-h_1}^{t-h_m} \dot{x}^T(s)R_1\dot{x}(s) \, ds - a_2 \int_{t-h_1}^{t-h_m} \dot{x}^T(s)R_2\dot{x}(s) \, ds - a_3 \int_{t-h_1}^{t-h_m} \dot{x}^T(s)R_3\dot{x}(s) \, ds + \rho^T(\eta)\Phi(\eta)
\]
\[
- \rho^T(\eta)\Phi(\eta) + \gamma^2 I\omega^T(t)\omega(t) - \gamma^2 I\omega^T(t)\omega(t) - z^T(t)z(t) + \zeta^T(t)z(t),
\]
\[
\leq \eta^T(t) \left( \Xi_1 - \Xi_2 - \Xi_3 + \Xi_4 + \frac{1}{2} \zeta \right) \eta(t) - \gamma^2 I\omega^T(t)\omega(t) + \theta(t).
\]

According to Lemma 3, the integral term \(-h_1\) \(\int_{t-h_1}^{t-h_m} \dot{x}^T(s)R_2\dot{x}(s) \, ds\) can be transformed as follows:

\[
-h_1 \int_{t-h_1}^{t-h_m} \dot{x}^T(s)R_2\dot{x}(s) \, ds = -(h_m - h_1) \int_{t-d(t)-h_1}^{t-h_m} \dot{x}^T(s)R_2\dot{x}(s) \, ds - (h_m - h_1) \int_{t-d(t)-h_1}^{t-h_m} \dot{x}^T(s)R_2\dot{x}(s) \, ds \leq \eta^T(t) \Xi_2 \eta(t).
\]

\[
\begin{align*}
-h_1 & \int_{t-h_1}^{t-h_m} \dot{x}^T(s)R_2\dot{x}(s) \, ds \leq 4x^T(t)R_1x(t) + 4x^T(t - h_1)R_1x(t) + 2x^T(t)R_1x(t - h_1) + 2x^T(t - h_1)R_1x(t) \\
& \quad - \frac{6}{h_1} \int_{t-h_1}^{t} \dot{x}^T(s) \, ds - \frac{6}{h_1} \int_{t-h_1}^{t} \dot{x}^T(s) \, ds R_1x(t) - \frac{6}{h_1} \int_{t-h_1}^{t} \dot{x}^T(s) \, ds R_1x(t) \\
& \quad - \frac{6}{h_2} \int_{t-h_1}^{t-h_2} \dot{x}^T(s) \, ds R_1x(t - h_1) - a_2 \int_{t-h_2}^{t-h_m} \dot{x}^T(s)R_2\dot{x}(s) \, ds \\
& \quad \leq 4x^T(t - h_m)R_2x(t - h_m) + 4x^T(t - h_2)R_2x(t - h_2) + 2x^T(t - h_m)R_2x(t - h_2) \\
& \quad + 2x^T(t - h_2)R_3x(t - h_2) - \frac{6}{a_2} \int_{t-h_2}^{t-h_m} \dot{x}^T(s) \, ds R_2x(t - h_2) \\
& \quad - \frac{6}{a_3} \int_{t-h_2}^{t-h_m} \dot{x}^T(s) \, ds R_2x(t - h_2) \\
& \quad \leq -\eta^T(t)\Xi_1 \eta(t),
\end{align*}
\]

where \(Q_{11} = H_1 + H_2 + H_3 + He(PA)\).
\[ \Xi_1 = \begin{bmatrix} Q_{11} & PB_1 K D_2 & 0 & 0 & 0 & 0 & 0 & 0 & -PB_1 K & PC_1 \\ * & \delta D_2^T \phi D_2 & 0 & 0 & 0 & 0 & 0 & 0 & -\delta D_2^T V & 0 \\ * & * & -H_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & -H_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -H_3 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & -12R_1 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & -12R_2 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & -12R_2 & 0 & 0 \\ * & * & * & * & * & * & * & * & -12R_3 & 0 & 0 \\ * & * & * & * & * & * & * & * & * & (\delta - 1) \Phi & 0 \\ * & * & * & * & * & * & * & * & * & * & -c^2 I \end{bmatrix} \]

\[ \Xi_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & F_{22} & F_{23} & F_{24} & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & 4R_2 & F_{34} & 0 & 0 & -6R_2 & F_{38} & 0 & 0 \\ * & * & * & 4R_2 & 0 & 0 & F_{47} & -6R_2 & 0 & 0 \\ * & * & * & * & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & 12R_2 & 0 & 0 & 0 \\ * & * & * & * & * & * & 12R_2 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & * & 0 & 0 \\ * & * & * & * & * & * & * & * & * & 0 \end{bmatrix} \]

\[ \Xi_3 = \begin{bmatrix} 4R_1 & 0 & 2R_1 & 0 & 0 & -6R_1 & 0 & 0 & 0 & 0 \\ * & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & 4R_1 & 0 & 0 & -6R_1 & 0 & 0 & 0 & 0 \\ * & * & * & 4R_3 & 2R_3 & 0 & 0 & -6R_1 & 0 & 0 \\ * & * & * & 4R_3 & 0 & 0 & 0 & -6R_1 & 0 & 0 \\ * & * & * & * & 12R_1 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & 12R_3 & 0 & 0 \\ * & * & * & * & * & * & * & * & 0 & 0 \\ * & * & * & * & * & * & * & * & * & 0 \end{bmatrix} \]

\[ \Xi_1 = \begin{bmatrix} h_1 R_1 A & h_1 R_1 B_1 K D_2 & 0 & 0 & 0 & 0 & 0 & 0 & -h_1 R_1 B_1 K & h_1 R_1 C_1 \end{bmatrix} \]

\[ \Xi_2 = \begin{bmatrix} a_2 R_2 A & a_2 R_2 B_1 K D_2 & 0 & 0 & 0 & 0 & 0 & 0 & -a_2 R_2 B_1 K & a_2 R_2 C_1 \end{bmatrix} \]

\[ \Xi_3 = \begin{bmatrix} a_3 R_3 A & a_3 R_3 B_1 K D_2 & 0 & 0 & 0 & 0 & 0 & 0 & -a_3 R_3 B_1 K & a_2 R_3 C_1 \end{bmatrix} \]

\[ \Xi = \begin{bmatrix} D_1^T & B_2 K D_2 & 0 & 0 & 0 & 0 & 0 & -B_2 K & C_2 \end{bmatrix} \]
To make closed-loop system (3) meet the $H_{\infty}$ applications, we can conclude
\[
\Xi_1 - \Xi_2 - \Xi_3 + \Xi_1^T R_1^{-1} \Xi_1 + \Xi_2^T R_2^{-1} \Xi_2 + \Xi_3^T R_3^{-1} \Xi_3 + \zeta^T,
\]
\[
\zeta < 0.
\]

(18)

Through Schur supplement for (18), we can obtain
\[
\begin{bmatrix}
W_{11} & PB_1 KD_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
* & \delta D_2^T V D_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
* & * & -H_1 & 0 & 0 & 0 & 0 & 0 \\
* & * & * & -H_2 & 0 & 0 & 0 & 0 \\
* & * & * & * & -H_3 & 0 & 0 & 0 \\
* & * & * & * & * & 0 & 0 & 0 \\
* & * & * & * & * & * & 0 & 0 \\
\end{bmatrix}
\]

(19)

\[
\begin{bmatrix}
-W_{11} & -PB_1 K C_1 & h_1 (R_1 A)^T & a_2 (R_2 A)^T & a_3 (R_3 A)^T & D_1^T \\
-\delta D_2^T V & 0 & h_1 (R_1 B_1 K D_2)^T & a_2 (R_2 B_1 K D_2)^T & a_3 (R_3 B_1 K D_2)^T & (B_2 K D_2)^T \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
< 0.
\]
Multiplying left by $\Lambda$ and right by $\Lambda^T$, we have

\[
\begin{bmatrix}
W_{11} & h_1 (R_1 A)^T & a_2 (R_2 A)^T & a_3 (R_2 A)^T & D_1^T & 6R_1 & 0 & 0 & 0 \\
* & -R_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
* & * & -R_2 & 0 & 0 & 0 & 0 & 0 & 0 \\
* & * & * & -R_3 & 0 & 0 & 0 & 0 & 0 \\
* & * & * & * & -I & 0 & 0 & 0 & 0 \\
* & * & * & * & * & -12R_1 & 0 & 0 & 0 \\
* & * & * & * & * & * & -12R_2 & 0 & 0 \\
* & * & * & * & * & * & * & -12R_3 & 0 \\
* & * & * & * & * & * & * & * & * \\
* & * & * & * & * & * & * & * & * \\
* & * & * & * & * & * & * & * & * \\
* & * & * & * & * & * & * & * & * \\
* & * & * & * & * & * & * & * & * \\
* & * & * & * & * & * & * & * & * \\
\end{bmatrix}
\]

(20)

\[
\begin{bmatrix}
-PB_1 K & PC_1 & PB_1 KD_2 & -2R_1 & 0 & 0 \\
-h_1 PB_1 K & h_1 (R_1 C_1) & h_1 PB_1 KD_2 & 0 & 0 & 0 \\
-a_2 PB_1 K & a_2 (R_2 C_1) & a_2 PB_1 KD_2 & 0 & 0 & 0 \\
-a_3 PB_1 K & a_3 (R_3 C_1) & a_3 PB_1 KD_2 & 0 & 0 & 0 \\
-B_2 S & C_2 & B_2 SD_2 & 0 & 0 & 0 \\
0 & 0 & 0 & 6R_1^T & 0 & 0 \\
0 & 0 & -F_{27}^T & 6R_2^T & -F_{47}^T & 0 \\
0 & 0 & -F_{28}^T & -F_{38}^T & 6R_3^T & 0 \\
0 & 0 & 0 & 0 & 6R_4^T & 6R_5^T \\
(\delta - 1) V & 0 & -\delta V D_2 & 0 & 0 & 0 \\
* & -\gamma^2 I & 0 & 0 & 0 & 0 \\
* & * & W_{22} & -F_{23} & -F_{24} & 0 \\
* & * & * & W_{33} & -F_{34} & 0 \\
* & * & * & * & W_{44} & -2R_3 \\
* & * & * & * & * & W_{55} \\
\end{bmatrix}
\]
where

\[
\Lambda = \begin{bmatrix}
I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 \\
0 & I & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 \\
0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & I \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}.
\]

Let \( K = Z^{-1} S \), and (18) can be rewritten as follows:

\[
\begin{bmatrix}
\Gamma_{11} & \Gamma_{12} \\
* & \Gamma_{22}
\end{bmatrix} + H e \begin{bmatrix}
I_g \\
0_{6 \times 9}
\end{bmatrix} \begin{bmatrix}
PB_1 - B_1 Z \\
h_1 (R_1 B_1 - B_1 Z) \\
a_2 (R_2 B_1 - B_1 Z) \\
a_3 (R_3 B_1 - B_1 Z) \\
B_2 - B_2 Z \\
0 \\
0 \\
0
\end{bmatrix} \begin{bmatrix}
-Z^{-1} S & 0 & -Z^{-1} S D_2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
0_{6 \times 9} \\
I_6
\end{bmatrix} < 0.
\]

(22)

Applying Lemma 1, we can obtain

\[
H e \begin{bmatrix}
I_g \\
0_{6 \times 9}
\end{bmatrix} H = \begin{bmatrix}
PB_1 - B_1 Z \\
h_1 (R_1 B_1 - B_1 Z) \\
a_2 (R_2 B_1 - B_1 Z) \\
a_3 (R_3 B_1 - B_1 Z) \\
B_2 - B_2 Z \\
0 \\
0 \\
0 \\
0
\end{bmatrix} \begin{bmatrix}
-Z^{-1} S & 0 & -Z^{-1} S D_2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
0_{6 \times 9} \\
I_6
\end{bmatrix}
\]

(23)
Combining (20) and (22) can lead to
\[
\begin{bmatrix} \Gamma_{11} & \Gamma_{12} & 0 \\ \ast & \Gamma_{22} & E^T \ast \\ \ast & \ast & H^T J^{-1} H \end{bmatrix} < 0,
\]
(24)
where
\[
E = \begin{bmatrix} -Z^{-1} S & 0 \end{bmatrix}, \quad H = \begin{bmatrix} PB_1 - B_1 Z \\ \sqrt{\alpha_1} (R_1 B_1 - B_1 Z) \\ \sqrt{\alpha_2} (R_2 B_1 - B_1 Z) \\ \sqrt{\alpha_3} (R_3 B_1 - B_1 Z) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}.
\]

Through Lemma 2 and Schur complement to (24), we can obtain
\[
\begin{bmatrix} \Gamma_{11} + J & \Gamma_{12} & 0 \\ \ast & \Gamma_{22} & E^T G^T B_1^T B_1^T \\ \ast & \ast & H e (B_1^T B_1^T G) \end{bmatrix} < 0.
\]
(26)

So, we can obtain that
\[
\eta^T(t) \left[ \Xi_1 - \Xi_2 - \Xi_3 + \Xi_4 + \Xi_5 + \Xi_6 + \Xi_7 + \Xi_8 + \Xi_9 + \xi^T \xi \right],
\]
\[
\eta(t) < 0,
\]
(27)
and we can conclude
\[
\dot{V}(t) + \delta V(t) \leq \eta^T(t) \left[ \Xi_1 - \Xi_2 - \Xi_3 + \Xi_4 + \Xi_5 + \Xi_6 + \Xi_7 + \Xi_8 + \Xi_9 + \xi^T \xi \right] \eta(t) \eta(t) - \gamma^T z(t) + \gamma^T \eta(t) \| \omega(t) \|_2 + \Theta(t).
\]
(28)

Applying comparison lemma [34] to (26),
\[
V(t) \leq e^{-\delta t} \left( V(0) + \frac{\beta}{\delta} \left( 1 - e^{\delta t} \right) \| \omega(t) \|_2 \right),
\]
(29)
where \( \psi(t) = \int_0^t e^{-\delta (t-s)} \left( \beta e^{-\alpha s} \right) ds \).

We consider the following situations by category.

(i) If \( \beta = 0 \), we can conclude \( \psi(t) = 0 \):
\[
V(t) \leq e^{-\delta t} \left( V(0) - \frac{\beta}{\delta} \| \omega(t) \|_2 \right) + \frac{\beta}{\delta} \| \omega(t) \|_2.
\]
(30)

(ii) If \( \beta > 0, \alpha = 0 \), we can conclude \( \psi(t) = \gamma/\delta \left( 1 - e^{\delta t} \right) \):
\[
V(t) \leq e^{-\delta t} \left( V(0) - \frac{\beta}{\delta} \| \omega(t) \|_2 \right) + \frac{\beta}{\delta} \| \omega(t) \|_2.
\]
(31)

(iii) If \( \beta > 0, \alpha > 0, \delta - \alpha \ln \epsilon = 0 \), we can conclude \( \psi(t) = \beta t e^{-\alpha t} \):
\[
V(t) \leq e^{-\delta t} \left( V(0) - \frac{\beta}{\delta} \| \omega(t) \|_2 + \beta t \right) + \frac{\beta}{\delta} \| \omega(t) \|_2.
\]
(32)

(iv) If \( \beta > 0, \alpha > 0, \delta - \alpha \ln \epsilon > 0 \), we can conclude \( \psi(t) = \beta/\delta - \alpha \ln \epsilon (e^{-\alpha t} - e^{-\delta t}) \):
\[
V(t) \leq e^{-\delta t} \left( V(0) - \frac{\beta}{\delta} \| \omega(t) \|_2 + \beta t - \frac{\beta}{\delta - \alpha \ln \epsilon} \right) + \frac{\beta}{\delta} \| \omega(t) \|_2
+ \frac{\beta}{\delta - \alpha \ln \epsilon} e^{-\alpha t}.
\]
(33)

Define \( \psi_{\text{max}} = \max \psi(t) \) and union (30)–(33) can lead:
\[
\psi_{\text{max}} = \begin{cases} 0, & \beta = 0, \\
\frac{\beta}{\delta}, & \beta > 0, \alpha > 0, \\
\frac{\beta e^{\alpha t_0}}{\delta - \alpha \ln \epsilon}, & \beta > 0, \alpha > 0, \delta - \alpha \ln \epsilon = 0, \\
\frac{\beta e^{\alpha t_0}}{\delta - \alpha \ln \epsilon}, & \beta > 0, \alpha > 0, \delta - \alpha \ln \epsilon \neq 0. \end{cases}
\]
(34)

Accordingly, LKF can lead \( x^T(t) P x(t) \leq V(t) \). If \( \omega(t) = 0 \), we can obtain
\[
x^T(t) P x(t) \leq V(t) \leq V(0) + \psi_{\text{max}},
\]
(35)
and we delimit
\[
\mathfrak{F} = \sqrt{\frac{V(0) \psi_{\text{max}}}{\lambda_{\min}} (P)}.
\]
(36)

Accordingly, (34) and (35) can lead:
\[
x(t) \in \{ x : \| x(t) \| \leq \mathfrak{F} \}, \quad t > 0.
\]
(37)

Meanwhile, if \( \omega(t) = 0 \), accordingly, (36) can lead:
\[
\lim_{t \to \infty} V(t) \leq \begin{cases} \frac{\beta}{\delta}, & \beta > 0, \alpha = 0, \\
0, & \text{otherwise}, \end{cases}
\]
(38)
when \( t \to \infty \), (12) exponentially converges to the bounded region.
\[ * = \begin{cases} x(t) \in \mathbb{R}^{n} : \|x(t)\| \leq \frac{\beta}{\delta \lambda_{\min}(P)}, & \beta > 0, \alpha = 0, \\ 0, & \text{otherwise.} \end{cases} \]  

Then, we can get the closed-loop system (3) is GUUB when \( t \to \infty, \omega(t) = 0 \) the system state exponentially converges to the bounded area. At the same time, \( \|z(t)\| < \|\omega(t)\| \) at the zero-initial conditions is obtained.

**Remark 1.** Compared with [15], this paper has three different characteristics. (1) A mixed event triggering mechanism, in which absolute trigger mechanism is added to the relative to the trigger term. (2) The concept of the time-delay partitions was applied to build a LKF. (3) The external disturbance is added to the original system and Hoo performance index can be obtained. The purpose of the three improved views is to make the system robust.

**Remark 2.** Another class of method is reducing the conservatism of simple LKF. The augmented LKF is established,

\[
\xi_1(t) = \begin{bmatrix} x^T(t) & x^T(t-h_1) & x^T(t-h_2) \end{bmatrix} \int_{t-h_1}^{t} x^T(s) \, ds \int_{t-h_2}^{t} x^T(s) \, ds \xi_2(t) = \begin{bmatrix} x^T(t) & x^T(t) \end{bmatrix}. \]

**4. Simulation**

This section provides two numerical simulation examples. The first example shows that the proposed method is effective. The second example shows the dynamic response of the system in the event-driven mode.

**Example 1.** Given the following parameters,

\[
A = \begin{bmatrix} -0.2 & -0.1 \\ 0.2 & -0.5 \end{bmatrix},

B_1 = \begin{bmatrix} 1 \\ 1 \end{bmatrix},

C_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix},

D_1 = \begin{bmatrix} 0.3 & 1 \end{bmatrix},

D_2 = \begin{bmatrix} 1 & 0 \end{bmatrix},

B_2 = 0.1.
\]

Apply Theorem 1 with \( h = 0.01 \, \text{s}, \, d_M = 0.5, \) and \( \gamma = 50. \) With the change of \( \delta, \) the corresponding controller gain \( K \) and event-driven matrix \( \Phi \) are listed in Table 1.

**Table 1:** The controller gain \( K \) and the weight matrix \( \Phi. \)

| \( \delta \) | \( K \) | \( \Phi \) |
|---|---|---|
| 0.1 | -0.0684 | 163 |
| 0.2 | -0.0130 | 58.7500 |
| 0.3 | -0.0114 | 27.7632 |

in which it contains not only the state vector but also the derivative of the state. Meanwhile, the free-weight matrix inequality is raised in the study of integral inequalities. The free-weight matrix inequality adds some freedoms to the system based on the Wirtinger inequality. Constructing a suitable LKF by combining the two methods above, the function can be selected as

\[
V(t) = \xi_1^T(t)P\xi_1(t) + \int_{t-h_1}^{t} \xi_2^T(s)H_1\xi_2(s) \, ds + \int_{t-h_2}^{t} \xi_2^T(s)H_2\xi_2(s) \, ds + \int_{t-h_1}^{t} \xi_2^T(s)H_3\xi_2(s) \, ds + \int_{t-h_2}^{t} \xi_2^T(s)H_4\xi_2(s) \, ds,
\]

where

\[
\delta = 0.2, \alpha_1 = 0, \beta = 0.1, \alpha = 0.5, \varepsilon = e, \text{ and } \varepsilon_0 = 0.01.
\]

**Example 2.** Given \( \delta = 0.1, \, h_1 = 0.01, \, h_2 = 0.15, \, h_M = 0.1, \) controller gain \( K = -0.00684, \) weight matrix \( \Phi = 2921.3, \) \( h = 0.01, \) and \( \gamma = 50. \) According to the above conditions, system (1) is stable in the event-driven mode. \( x \) initial conditions are \( x(0) = \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \omega(t) = 0.09 \sin 2.0 \times t. \)

If \( \delta = 0.1, \beta = 0 \) result is shown in following figures. According to the above set parameters in the paper, some simulation results are shown in Figure 1.

From Figure 1, we can find that the system actually works under the relative trigger mechanism. When the output error reaches a certain threshold, the system state updates and then presents a periodic update state. The length of update interval will depend on the setting of \( \delta \) value.

If \( \delta = 0, \beta = 0.3 \) result is shown in Figure 2.

From Figure 2, we can find that the actual operation of the system is under the absolute trigger mechanism, and the trigger threshold is independent of the system state. Depending on the setting of \( \beta \) value, it is obvious that the update time of the system is earlier and the update interval is denser.

If \( \delta = 0.1, \beta = 0.3 \) result is shown in Figure 3.

From Figure 3, we can find that the system actually works under the mixed trigger mechanism. The trigger
threshold is related not only to the system state but also to the initially set $\beta$ value. We can see that the number of system updates is significantly reduced and the update interval is longer. Through the above simulation, it can be found that different trigger mechanisms can stabilize the system, but the update time of the system state is obviously different. Among them, the hybrid trigger mechanism proposed in this paper has more effective results, which can greatly reduce the network burden and save network bandwidth compared with the other two trigger methods.
5. Conclusion

This paper has investigated the event-driven problem about NCSs. A mixed event trigger mechanism is introduced, which contains absolute trigger mechanism and relative trigger. The event triggering mechanism can be expressed by a time-delay model. The coupling of the system is reduced by introducing additional parameters and matrices. The sufficient condition can be obtained by LMI. By using the Wirtinger inequality method, relatively event-driven controller can be obtained, which meets an $H_\infty$ performance index level of NCSs. Finally, two numerical simulation examples illustrate the effectiveness of the proposed method. In networked control systems, besides time delay, packet loss and quantization are also important factors that affect system performance. How to comprehensively consider the above two factors combined with trigger mechanism will be the focus of future work.

Data Availability

The data used to support the findings of this study are included within the article. Because it is a numerical simulation example, readers can get the same results as this article by using the LMI toolbox of Matlab and the theorem given in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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