Secure Event-Triggered Mechanism for Networked Control Systems under Injection Cyber-Attacks

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1. Introduction

As one of the greatest inventions in the 21st century, the popularity of the Internet has brought significant changes and influences on people’s production and lives. With the further development of the Internet, the emergence of big data better reflects the advantages of the Internet. Better handling of big data and better transmission of data have become a hot direction for future research [1, 2]. Data transmission is ultimately reflected in network communication applications (see Figure 1). Thus, network communication technology has been widely used in industrial and military fields. It is a current trend to add components of control systems to these applications through the Internet [3–5].

However, in control theory, signal transmission usually relies on network communication techniques. Therefore, this brings the control system into contact with the Internet [6, 7]. Signal transmission between the components of NCSs can be carried out through the network. When we design and implement the corresponding control system, we can reduce the influence of the signal transmission between the components of NCSs through the network [8]. This approach allows NCSs to reduce their complexity and overall cost-effectiveness. Unnecessary wiring between components is eliminated, which effectively reduces the NCS complexity and overall cost. Therefore, NCSs have become one of the hot issues of current research [9, 10]. In [8], Zhang proposed a novel robust event-triggered fault-tolerant automatic steering control strategy for autonomous land vehicles to achieve path tracking and vehicle lateral motion control under in-vehicle network delay. In [9], the problem of fault-tolerant sampled-data control for an NCS with random time delays and actuator faults was investigated. In [10], the authors studied the application of NCSs to high-speed trains.

On the one hand, the data on the NCS can be effectively shared, which facilitates the fusion of all the information in an ample actual physical space. This way, if the system needs to be upgraded or changed, sensors, controllers, and actuators will need to be added or removed without significant changes to the system architecture [11]. Most importantly, connecting cyber-space to physical space makes real-time control feasible. Therefore, this makes the NCSs gradually
tend to control artificial intelligence and the arrival of the era when everything is connected [12]. On the other hand, the transmission of signals in the communication process of the network is not always secure. Normal loss or delay of signals in network communications is a common phenomenon. We think this phenomenon is acceptable and can be controlled. There has been a malicious attack or sabotage of communication equipment or control systems. We believe this behavior is a cyber-attack, and the person that launched the cyber-attack is a hacker [13]. At present, common cyber-attacks are mainly divided into the following categories: random cyber-attacks [14–16], deception cyber-attacks [17–19], jamming attacks [20, 21], and DoS attacks [22–24].

Thus, effectively countering and defending against hacker attacks is also one of the hot topics. In [15], Liu focused on the controller design problem of NCSs, and a hybrid-triggering communication strategy was employed to save the limited communication resources. In [18], the authors investigated the $H_{\infty}$ memory sample-data control issue of the T-S fuzzy NCSs with multiple asynchronous deception attacks. In [21], the event-based controller synthesis problem of NCSs under resilient event-triggering communication schemes and periodic DoS jamming attacks was studied. In [24], Feng aimed to explore the tradeoffs between system resilience and network bandwidth capacity.

Based on the above discussion, this paper mainly studies the security issues of NCSs. When hackers attack the system, the ETM controller we designed can effectively ensure the stability of the system. Compared with existing works [25–27], the main contributions of this paper are as follows:

(1) According to the advent of the Internet and the big data era, the security issues of NCSs are being studied. A new ICA is proposed to study the communication security of the system.

(2) A more general LKF is constructed by utilizing the time-delay phenomenon inside the system. According to the characteristics of the sampling period, the constructed LKF contains more sampling information. In addition, the positive definiteness constraint on the initial matrices is further relaxed.

(3) For ICAs launched by hackers, we designed an ETM controller to ensure the AS of the NCS.

2. Preliminaries

In this article, we research the following NCSs:

$$\dot{x}(t) = Ax(t) + B\bar{u}(t),$$  \hspace{1cm} (1)

where $x(t) \in \mathbb{R}^n$ is the current state vector of the system; $\bar{u}(t) \in \mathbb{R}^m$ is the signal to control the input; and $A$ and $B$ are constant matrices.

The control signals are represented as follows:

$$\bar{u}(t) = u(t) + f(t),$$  \hspace{1cm} (2)

where $f(t)$ is the injection attack function.

Remark 1. The popularity of the Internet has made the processing of big data more efficient and faster. Therefore, studying the control of the system based on network communication has become a hot topic of research. There are always some signal fluctuations in the communication process of the control signal. Normal signal fluctuations of the control signal are acceptable. However, some abnormal signals are often injected into the system to destroy the systems’ performance, which we call ICAs. As shown in Figure 2, the sensor communicates with the actuator through network communication with signal transmission. During this process, the system may be maliciously attacked by hackers. Therefore, this paper designs a suitable ETM controller for the communication security of NCSs to ensure the system’s regular operation.

![Figure 1: Internet communication topology.](image-url)
Then, the controller can be designed as
\[ u(t) = Kx(t_k h), \quad t \in (t_k h, t_{k+1} h), \] (3)
where \( K \) is a controller gain matrix.

In this framework, the sensor is time-triggered while the controller, the zero-order hold (ZOH), and the actuator are event-triggered.

We will illustrate our proposed security-orient resilient triggering strategy as follows:
\[ t_{k+1} h = t_k h + \min \left\{ \ell h | e(t_k) \Phi e(t_k) - \delta x^T(t_k h) \Phi x(t_k h) > 0 \right\}, \] (4)
where \( e(t_k) = x(t_k h + \ell h) - x(t_k h) \) and \( \Phi > 0 \). \( x(t_k h) \) is the latest transmitted signal at the latest triggering time \( t_k h \). The sampling interval is divided into \( [t_k h + \eta_1, t_{k+1} h + \eta_2(t_k)] \). \( \eta \) satisfies \( [t_k h + \eta_1, t_{k+1} h + \eta_2(t_k)] = \cup_{\ell \in \Omega} t_k \ell \), where \( \Omega = \{ t_k h + \ell h + \eta_1, t_k h + \ell h + h + \eta_2, \ell + 1 \} \), \( \ell = 0, 1, \ldots, \eta \), and \( \eta = t_{k+1} - t_k - 1 \). We define \( d(t) = t - t_k h - \ell h \) and \( 0 \leq \eta_1 \leq \ell \leq \rho(t) \leq \rho_1 \), in which \( \rho \leq h + \eta_2(t_k) \). From the definitions of \( \rho(t) \) and \( e(t_k) \), we can obtain \( x(t_k h) = x(t - \rho(t)) + e(t_k) \).

Then, we can obtain
\[ \bar{u}(t) = K \left[ x(t - \rho(t)) - e(t_k) + f(t) \right], \] (5)
From equations (1) and (5), the closed-loop system as follows:
\[ x'(t) = Ax(t) + BK \left[ x(t - \rho(t)) - e(t_k) + f(t) \right], \] (6)
Assumption 1. ([19]). Any \( u_1(t) \) and \( u_2(t) \in \mathbb{R}^{n_2} \) meets the Lipschitz condition with the following form:
\[ f^T(t) f(t) \leq x^T(t) F^T F x(t), \] (7)
where \( F \) is the upper bound of \( f(\cdot) \).

Lemma 1 (see [28]). Given \( \Omega > 0 \) and integrate \( e(s) \) over the interval \([a, b] \rightarrow \mathbb{R}^{n_2} \), we know the matrix inequality holds:
\[ -(b - a)^b \int_a^b e(s) \Omega e(s) ds \geq -\zeta^T \Omega \zeta - 3\Omega^T \Omega \omega, \] (8)
where \( \zeta = x(b) - x(a) \) and \( \omega = x(b) + x(a) - 2 \int_a^b x(s)/b - a \).

3. Main Results

**Theorem 1.** Given positive scalars \( \epsilon, \nu, a, h_m, \) and \( h_M, \) system (6) is AS; if there exist symmetric matrices \( P_1, P_2 \geq 0 \) and \( M_1 > 0, M_2 \), then any matrices \( R_1, R_2, \) and \( Y_i (i = 1, 2, 3) \) with appropriate dimensions satisfy the following LMIs:
\[ P_1 + \rho P_2 > 0, \]
\[ M_1 + \rho M_2 > 0, \]
\[ \begin{bmatrix} \Xi_{p(t)} & \Pi_1 & \Pi_2^T \\ \ast & -\epsilon_1 I & 0 \\ \ast & \ast & -\epsilon_2^{-1} I \end{bmatrix} < 0, \]
where other symbols and associated equations are expressed in Appendix B.

**Proof.** Construct a suitable LKF as follows:
\[ V(x(t)) = \sum_i V_i(x_i), \quad t \in [t_k h, t_{k+1} h], \] (12)
where
\[ V_1(x_i) = a^T(t) P_{\rho(t)} a(t), \]
\[ V_2(x_i) = \tilde{h}_2 h_2 \xi^T(t) M_{\rho(t)} \xi(t), \]
\[ V_3(x_i) = \tilde{h}_3 h_3 \int_{t_p - \rho}^{t_p} \xi^T(t) R_1 \xi(t) ds, \]
\[ V_4(x_i) = h_4 M_{\rho(t)} \int_{t_p - \rho}^{t_p} \xi^T(t) R_2 \xi(t) ds, \]
\[ P_{\rho(t)}, M_{\rho(t)}, \alpha(t), \delta(t), \tilde{h}_4, \tilde{h}_3, \text{ and } \xi(t) \text{ are listed in Appendix A.} \]

Then, we can obtain the derivative of \( V(x(t)) \) as follows:
\[ \frac{dV(x(t))}{dt} = \sum_i \frac{dV_i(x_i)}{dt}, \quad t \in [t_k h, t_{k+1} h], \]
\[ \frac{dV(x(t))}{dt} = 2a^T(t) P_{\rho(t)} a(t) - \dot{\rho}(t) a^T(t) P_{\rho(t)} a(t), \]
\[ = -\dot{\rho}(t) a^T(t) P_{\rho(t)} a(t) + 2a^T(t) P_{\rho(t)} \begin{bmatrix} \dot{x}(t) \\ x(t - \rho) \end{bmatrix}, \]
\[ = \xi^T(t) \mathcal{X}_1 \xi(t), \] (13)
\[
\frac{dV_2(x_t)}{dt} = (\tilde{h}_k - h_k)\delta^T(t)M_{P(t)}\delta(t) - \dot{\rho}(t)\tilde{h}_k h_k \\
\times \delta^T(t)M_{2}\delta(t) + 2\delta^T(t)M_{P(t)}\dot{\delta}(t), \\
= (\tilde{h}_k - h_k)\delta^T(t)M_{P(t)}\delta(t) - \dot{\rho}(t)\tilde{h}_k h_k \\
\times \delta^T(t)M_{2}\delta(t) + 2\delta(t)M_{P(t)} \begin{bmatrix} x(t - \rho) & 0 \\ 0 & 0 \end{bmatrix}, \\
= \xi^T(t)\Xi_2\xi(t), \\
\]

(14)

\[
-h_M \int_{t-\rho}^{t_{k-h}} \hat{x}^T(s) R_1 x(s) ds \leq \frac{h_M}{h_k} \left[ x(t_k h - \rho) - x(t - \rho) x(t_k h - \rho) + x(t - \rho) - 2 \int_{t-\rho}^{t_{k-h}} x(s) h_k ds \right] \\
\times \begin{bmatrix} R_1 & 0 \\ 0 & 3R_2 \end{bmatrix} \left[ x(t_k h - \rho) - x(t - \rho) x(t_k h - \rho) + x(t - \rho) - 2 \int_{t-\rho}^{t_{k-h}} x(s) h_k ds \right] \\
\leq \frac{h_M}{h_m \xi^T(t) \Omega_b^T R \Omega_a \tilde{\xi}(t)}.
\]

(17)

Thus, we know that the following inequality holds:

\[
\frac{dV_3(x_t)}{dt} + \frac{dV_4(x_t)}{dt} \leq \xi^T(t) \left( h_M e^{R_2 h_k R_1 h_k} + \frac{h_M}{h_k \Omega_a \Omega_1 \Omega_a} + \frac{h_M}{h_k \Omega_a \Omega_2 \Omega_b} \right) \xi(t) = \xi^T(t) \Xi_2 \xi(t).
\]

(19)

Based on system (6), for any matrices \(Y_1, Y_2, Y_3\), we have the following equation:

\[
0 = 2 \left[ e^T(t_k) Y_1 x + x^T(t_k h) Y_2 + x^T(t - \rho(t)) Y_3 \right] \\
\times \left[ A x(t) + BK x(t - \rho(t)) + BK f(t) \right],
\]

(20)

According to Assumption 1, we have the following equation:

\[
2BK f(t) \leq \xi^T(t) \left( d\Pi_1 \Pi_1^T + \delta \Pi_2 \right) \xi(t).
\]

(21)

Considering the rules of the designed event-triggered schemes, the following equation holds:

\[
e(t_k) \Phi e(t_k) - \delta x^T(t_k h) \Phi x(t_k h) = \xi^T(t) \Theta \xi(t).
\]

(22)
\[
\begin{bmatrix}
\Xi_{p,t}^{h_1} & \Pi_1 & \Pi_2^T \\
* & -\epsilon_1 I & 0 \\
* & * & -\epsilon_2^{-1} I 
\end{bmatrix} < 0. 
\tag{24}
\]

Therefore, it follows \(\sum_i dV_i(x_i)/dt < 0\). Finally, system (6) tends to AS. \(\square\)

**Remark 2.** Compared with existing works [26, 27, 29], this paper constructs a more general LKF for the time-delay phenomenon in systems: (1) when \(\rho(t) = \rho\), the constructed LKF will degenerate into being independent of time delay and (2) when \(\rho(t) = 0\), the LKF contains correct time-delay information and time-delay derivative information. This method can introduce more information storage and reduce the conservativeness of the criterion.

**Remark 3.** Different from the traditional BLFs, \(V_2(x_i)\) constructed in this paper contains more sampling moments information \(\bar{h}_k\) and \(\bar{d}_k\). When \(\lim_{t \to +\infty} \bar{h}_k = \lim_{t \to +\infty} \bar{d}_k = 0\) holds, there is no constraint on the matrices \(M_{p(t)}\). The LKF constructed in this paper is a promotion and enhancement of the BLF in [30].

**Remark 4.** In this paper, we construct \(V_1(x_i)\) and \(V_4(x_i)\). Compared with the LKF in reference [30], \(V_3(x_i)\) and \(V_4(x_i)\) contain the sampling period \(h_m\) information and time-delay \(\rho\) information. Then, we obtain tighter upper bounds by scaling with appropriate integral inequalities, which ensures that the criterion is less conservative.

**Remark 5.** This paper analyzes the performance of the computer in the process of solving the LMIs. The computational complexity of Theorem 1 is \(7n^2 + 2n\). Then, based on Intel(R) Core(TM) i7-8700 CPU@3.20 GHz 3.19 GHz, pairs of large-scale LMIs are calculated.

**Theorem 2.** Given scalars \(\epsilon, \nu, \alpha, \psi, \psi_2, h_m, \) and \(h_M\), system (6) is AS; if there exist symmetric matrices \(P_1, P_2 > 0\), \(M_1 > 0\), and \(M_2\), any matrices \(R_1, R_2,\) and \(N\) with appropriate dimensions satisfy the following LMIs:

\[
\begin{align*}
\bar{P}_1 + \rho \bar{P}_2 &> 0, \\
\bar{M}_1 + \rho \bar{M}_2 &> 0,
\end{align*} 
\tag{25}
\]

\[
\begin{bmatrix}
\Xi_{p,t}^{h_1} & \tilde{\Pi}_1 & \tilde{\Pi}_2^T \\
* & -\epsilon_1 I & 0 \\
* & * & -\epsilon_2^{-1} I 
\end{bmatrix} < 0, 
\tag{26}
\]

\[
\rho(t) \in \{0, \rho\},
\]

\[
h_k \in \{h_m, h_M\},
\tag{27}
\]

where other symbols and associated equations are expressed in Appendix C.

| \(\delta\) | [25] | Theorem 2 | Improvement (%) |
|---|---|---|---|
| 0 | 1.6982 | 1.9601 | 13.3609 |
| 0.1 | 1.1596 | 1.4927 | 14.9496 |
| 0.2 | 0.9346 | 1.0854 | 13.8935 |
| 0.3 | 0.7621 | 1.0061 | 24.2521 |
| 0.4 | 0.6169 | 0.9592 | 35.6860 |
| 0.5 | 0.4894 | 0.6813 | 28.1667 |

**Table 1: MASPs \(h_M\) for different \(\delta\).**

**Proof.** the matrices are defined as \(K = NX^{-1}\) and \(\bar{\Phi} = X^{-\tau} \Phi X^{-1}\).

Then, other matrices are defined as follows:

\[
\begin{align*}
Y_1 &= X^{-1}, \\
Y_2 &= \psi_1 X^{-1}, \\
Y_3 &= \psi_2 X^{-1}, \\
\bar{P}_{\delta(t)} &= \text{diag}(X^T, X^T, X^T) P_{\delta(t)} \text{diag}(X, X, X), \\
\bar{M}_{\delta(t)} &= \text{diag}(X^T, X^T, X^T) M_{\delta(t)} \text{diag}(X, X, X), \\
\bar{R}_1 &= X^T R_1 X, \\
\bar{R}_1 &= X^T R_1 X.
\end{align*}
\tag{28}
\]

Premultiplying and postmultiplying (9) and (10) by \(\text{diag}(X^T, X^T, X^T)\) and \(\text{diag}(X, X, X)\), then according to Schur complement, we can derive the LMIs (25) and (26). The proof process is consistent with Theorem 1. \(\square\)

4. **Illustrative Example**

**Example 1.** Consider a NCS, the parameters are as follows [25]:

![Figure 3: State responses of the original system with control.](image-url)
4.1. Case A: The System Is in Normal State. In this case, our research system is operating normally in a safe state. When \( \rho = 0, F = 0, \) and \( h_m = 0.1, \) we solve for maximum acceptable sampling periods (MASPs) by using Theorem 2. It can be seen from Table 1 that the MASPs \( h_M \) under different \( \delta \) are better than reference [25]. When \( \delta = 0.3, \) the \( h_M = 1.0061 \) solved in this paper is 24.2521% higher than the result of reference [25].

To verify the validity of the criterion, we solve the controller gain matrix is \( K = \begin{bmatrix} 50.4168 & -17.8803 \end{bmatrix} \) by using the Yalmip toolbox in Matlab. Then, we set \( h_m = h_M = 0.01, \delta = 0.3, \) and \( x(0) = [-10, 7]^T; \) furthermore, the stability of the system is verified by plotting the state trajectory images of the system.

| \( \delta \) | [25] | Case A | Case B | Reduction (%) |
|---|---|---|---|---|
| 0 | 1.6982 | 1.9601 | 1.5039 | 23.2743 |
| 0.1 | 1.1596 | 1.4927 | 1.1725 | 21.4511 |
| 0.2 | 0.9346 | 1.0854 | 0.9967 | 8.1721 |
| 0.3 | 0.7621 | 1.0061 | 0.8916 | 11.3806 |
| 0.4 | 0.6169 | 0.9592 | 0.7109 | 25.8861 |
| 0.5 | 0.4894 | 0.6813 | 0.4593 | 32.5845 |

In Figure 3, we can see that with the increase in time, the running trajectory of the system will fluctuate. But it eventually converges on a steady state. This means that the controller we designed is suitable. In order to more intuitively reflect the effect of the controller designed in this paper, we also draw Figure 4 of the running trajectory of the system when the controller fails.
In addition, the release time distribution and control signal input are shown in Figures 5 and 6, respectively.

4.2. Case B: The System Is in Abnormal State. In this case, we conducted a simulation experiment, as in Case A. When $\rho = 0$, $h_m = h_M = 0.01$, and $F_1 = 0.1$, the MASPs solved by using Matlab are shown in Table 2. Table 2 shows that the performance of the system is reduced when the system is attacked. However, the method proposed in this paper can still ensure the stability of the system. Assuming $\delta = 0.3$, we solve $h_M = 1.0061$ when the system is running normally. However, solve for $h_M = 0.8916$ when ICA constraints the system. By comparing the results, we know that although 11.3806% reduces the performance, our criterion is still less conservative than the results in reference [25].

Then, when $\psi_1 = \psi_2 = 1$ the controller gain is $K = [27.8726 - 10.5776]$. Setting $\rho = 0$, $F_1 = 0.01$, and $\delta = 0.3$, the initial condition is $x(0) = [4, -1]^T$. We assume that the attack function injected by the hacker is $f(t) = [-\tanh(0.5x(t)), -\tanh(0.25x(t))]^T$. When the system is subjected to ICA, we plot the state trajectory of the system in Figure 7. Compared with the normal running trajectory in Figure 3, we can see that the system oscillates more obviously and can still reach a stable state eventually. Furthermore, the trajectory of the system in the case of controller failure is plotted in Figure 8.

Finally, we plot the release time distribution of the system in Figure 9 and the control signal input in Figure 10.

5. Conclusion

This paper has considered the secure stability issue of NCSs under ICA, which have important applications in network security. Firstly, a more general LKF has been constructed based on the time-delay phenomenon in the system. Secondly, a novel BLF has been developed depending on the sampling period, fully considering time delay and sampling information, and the initial constraints on the criteria on the matrices have been effectively relaxed. In addition, appropriate integral inequalities have been used, making the criteria less conservative in this paper. Then, a new ETM controller under ICA has been designed to control the AS of NCSs. Finally, a numerical experiment has verified the correctness and feasibility of the theory. In the future, we extend this method and safety control strategy to T-S fuzzy systems, switching systems, Markov hopping systems, and some other systems.

Notations

$\mathbb{R}^n$: $n$-Dimensional Euclidean space
$\mathbb{Z}^{m\times n}$: $n \times n$ real matrices
$I$: Identity matrix
$Q^n$: $n \times n$ real symmetric matrices
$\mathcal{H} > 0$: Denote that $\mathcal{H}$ is a real positive definite matrix
$\text{Sym} = X^T + X$, and $\text{diag} \{\cdots\}$: Block diagonal matrix.
Appendix

A

\[
\alpha(t) = \text{col} \left\{ x(t), \int_{t_{k-\rho}}^{t_k} x(s) \, ds, \int_{t_{k-\rho}}^{t_k} x(s) \, ds \right\},
\]

\[
\delta(t) = \text{col} \left\{ x(t-\rho), x(t_k-h-\rho), x(t_{k+1-h-\rho}) \right\},
\]

\[
P_{\rho(t)} = P_1 + (\rho - \rho(t))P_2,
\]

\[
M_{\rho(t)} = M_1 + (\rho - \rho(t))M_2,
\]

\[
\begin{align*}
\bar{h}_k &= t_{k+1} - t,
\end{align*}
\]

\[
\begin{align*}
\bar{h}_k &= t - t_k, \\
\end{align*}
\]

\[
\begin{align*}
\Phi &= \text{col} \{ e_1, 0, 0 \}, \\
\mathcal{R}_1 &= \begin{bmatrix} R_1 \\ 0 \\ 0 \end{bmatrix}, \\
\mathcal{R}_2 &= \begin{bmatrix} R_2 \\ 0 \\ 0 \end{bmatrix},
\end{align*}
\]

(A.2)

B

\[
\begin{align*}
\sum_{i=1}^{3} \Xi_i &= \sum_{i=1}^{3} \Xi_i + \text{Sym} \{ L \Phi \} + \Theta, \\
\Xi_1 &= \text{Sym} \left\{ \Phi_1^T P_{\rho(t)} \Phi_1 \right\} - \mu_1 \Phi_1^T P_2 \Phi_1, \\
\Xi_2 &= -h_{k} \Phi_1^T \tilde{M}_{\rho(t)} \Phi_3 + h_{k} \Phi_1^T \tilde{M}_{\rho(t)} \Phi_3 - \mu_1 h_{k} h_{k} \Phi_1^T \tilde{M}_2 \Phi_3, \\
\Xi_3 &= h_{M} e_1^T \left( h_{k} \mathcal{R}_2 - h_{k} \mathcal{R}_1 \right) e_1 + \frac{h_{M}}{h_{m} \Omega_a^T \mathcal{R}_1 \Omega_a} + \frac{h_{M}}{h_{m} \Omega_b^T \mathcal{R}_2 \Omega_b}, \\
\bar{L} &= e_{11}^T + \psi_1 e_{12}^T + \psi_2 e_{10}^T, \\
\bar{\psi} &= A \Phi e_1 + B N e_{10}, \\
\Theta &= e_{11}^T \Phi e_1 + \delta e_{19}^T \Phi e_5, \\
\Pi_1 &= \text{LBK}, \\
\Pi_2 &= \text{Fe}_3, \\
\Omega_a &= \text{col} \{ e_1 - e_2, e_3 + e_2 - 2e_3 \}, \\
\Omega_b &= \text{col} \{ e_4 - e_2, e_4 + e_2 + 2e_3 \}, \\
\Phi_1 &= \text{col} \{ e_1, h_{k} e_6, h_{k} e_9 \}, \\
\Phi_2 &= \text{col} \{ e_6, -e_2, e_2 \}, \\
\Phi_3 &= \text{col} \{ e_2, e_3, e_4 \}, \\
\Phi_4 &= \text{col} \{ e_7, 0, 0 \}, \\
\mathcal{R}_1 &= \begin{bmatrix} R_1 \\ 0 \\ 0 \end{bmatrix}, \\
\mathcal{R}_2 &= \begin{bmatrix} R_2 \\ 0 \\ 0 \end{bmatrix},
\end{align*}
\]

(A.3)
Data Availability
The data used to support this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest.

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