Research Article

Active-Varying Sampling-Based Fault Detection Filter Design for Networked Control Systems

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This paper is concerned with fault detection filter design for continuous-time networked control systems considering packet dropouts and network-induced delays. The active-varying sampling period method is introduced to establish a new discretized model for the considered networked control systems. The mutually exclusive distribution characteristic of packet dropouts and network-induced delays is made full use of to derive less conservative fault detection filter design criteria. Compared with the fault detection filter design adopting a constant sampling period, the proposed active-varying sampling-based fault detection filter design can improve the sensitivity of the residual signal to faults and shorten the needed time for fault detection. The simulation results illustrate the merits and effectiveness of the proposed fault detection filter design.

1. Introduction

Networked control systems (NCSs) are spatially distributed systems whose sensors, actuators, and controllers are connected via a communication network. NCSs have been the subject of intensive research, and many interesting research topics have been reported, such as packet dropouts and network-induced delays [1–7], event-triggered control design [8–10], networked predictive control systems [11, 12], finite-horizon filtering [13, 14], quantization effects [14–16], output feedback control [17, 18], and nonuniformly distributed delays [19], to mention a few.

In NCSs, the sensor is assumed to sample at a fixed nominal period. However, computer loads, networks, and sporadic faults may cause sampling period jitter. Then, it is of paramount importance to study time-varying sampling periods [20, 21]. It should be pointed out that the time-varying sampling periods considered in [20, 21] are induced by some external factors. Different from the time-varying sampling periods studied in [20, 21], the active-varying sampling periods were introduced in [22] to make full use of the network bandwidth.

For NCSs, the occurrence of faults is usually unavoidable. Then, it is interesting and important to study how to detect the occurrence of faults in time. Fault detection has been recognized as an important technique guaranteeing the safety and reliability of NCSs, and some nice results dealing with fault detection of NCSs have been reported [23, 24]. For example, Huang and Nguang [25] investigated robust fault estimation for NCSs with network-induced delays. Based on likelihood ratios for networked predictive control systems with random network-induced delays and clock asynchronism, Liu and Xia [26] proposed a fault detection and compensation scheme. Dong et al. [27] was concerned with the network-based robust fault detection problem for Takagi-Sugeno fuzzy systems with stochastic mixed time delays and successive packet dropouts.

Notice that the constant sampling period is considered in [23–27]. When dealing with fault detection for NCSs, if a constant sampling period h is adopted and the network is occupied by the most users, h should be large enough to avoid network congestion. Then, the network bandwidth cannot be sufficiently used when the network is idle. However, if the sensor can adjust the length of the sampling period actively

to make full use of the network bandwidth, the needed time for fault detection may be shortened. It is interesting and important to study fault detection for NCSs adopting the active-varying sampling periods. *For the problem of fault detection of NCSs, considering the active-varying sampling periods will introduce some difficulty for system modelling, and the active-varying sampling-based fault detection for NCSs has been paid no attention in the existing literature, which motivates the current study.*

For discrete-time or discretized NCSs, suppose that i_k is the sum of the number of consecutive packet dropouts and the length of network-induced delays, and i_m and i_M are known constants with $i_m \leq i_k \leq i_M$, $\bar{i} = \lfloor (i_m + i_M)/2 \rfloor$, where $\bar{i}$ is the largest integer smaller than or equal to $(i_m + i_M)/2$. Then one can conclude that at any instant k , $i_m \leq i_k \leq \bar{i}$ or $\bar{i} < i_k \leq i_M$. On the other hand, for the specific instant k , the events $i_m \leq i_k \leq \bar{i}$ and $\bar{i} < i_k \leq i_M$ cannot occur simultaneously; such phenomenon is named as mutually exclusive distribution in this paper. When dealing with fault detection for discretized NCSs, *how to make full use of the mutually exclusive distribution characteristic of packet dropouts and network-induced delays to derive less conservative results is of paramount importance, which is the second motivation of this paper.*

This paper is concerned with fault detection filter (FDF) design for continuous-time NCSs considering packet dropouts and network-induced delays. By introducing the active-varying sampling period method, a new discretized model for fault detection NCSs is established. Based on the newly established model, the problem of fault detection filter design is studied. Even if the considered NCSs reduce to systems considering a constant sampling period, the proposed fault detection filter design is still applicable.

The contributions of this paper are summarized as follows.

- (i) The active-varying sampling period method is introduced to establish a new discretized model for fault detection NCSs.
- (ii) Fault detection filter design criteria for NCSs with packet dropouts and network-induced delays are derived. The derived design criteria can guarantee the sensitivity of the residual signal to faults.
- (iii) The mutually exclusive distribution characteristic of packet dropouts and network-induced delays is made full use of to deal with fault detection of the considered NCSs, and the newly derived fault detection filter design criterion is proved to be less conservative.

The remainder of this paper is organized as follows. By introducing the active-varying sampling period method, Section 2 establishes a new discretized model for continuous-time NCSs with faults. Section 3 is concerned with the full order fault detection filter design. The simulation results are presented in Section 4. Conclusions are drawn in Section 5.

Notation. I and 0 represent an identity matrix and a zero matrix with appropriate dimensions, respectively. $*$ denotes the entries of a matrix implied by symmetry. Matrices, if not explicitly stated, are assumed to have appropriate dimensions.

2. Modelling for Active-Varying Sampling-Based NCSs

The continuous-time NCSs whose faults are to be detected are described by

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) + B_w\omega(t) + E_f f(t), \\ y(t) &= Cx(t),\end{aligned}\tag{1}$$

where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$, $y(t) \in \mathbb{R}^s$, $\omega(t) \in \mathbb{R}^v$, and $f(t) \in \mathbb{R}^q$ are the state vector, control input vector, measurement output, disturbance input, and fault signal, respectively; $\omega(t)$ is assumed to belong to $L_2[0, \infty)$; A , B , B_w , E_f , and C are known constant matrices with appropriate dimensions.

In this paper, we assume that the system (1) is controlled through a one-channel network; packet dropouts and network-induced delays occur in the plant-to-FDF channel; the sensor is both clock-driven and event-driven, while the FDF and the actuator are event-driven. It should be pointed out that the results in this paper can be extended to deal with NCSs considering both the plant-to-FDF channel and the FDF-to-actuator channel.

When the network is idle and occupied by the most users, suppose that the plant-to-FDF network-induced delays are d_1 and d_2 , respectively. If a constant sampling period is adopted and the network is occupied by the most users, one can choose d_2 as the sampling period to avoid network congestion. Suppose that t_k is the latest sampling instant, τ_k is the network-induced delays of the measurement output y_k ($y_k = Cx_k$ and x_k is the plant state at the instant t_k), the instant that y_k reaches the actuator is $\tilde{k}$, and h_k is the length of the k th sampling period.

In the following, we will propose the active-varying sampling period method (see also [22] for a similar method) to improve the sensitivity of the residual signal to faults and shorten the needed time for fault detection.

Partitioning $[d_1, d_2]$ into l equidistant small intervals (l is a positive integer), then the next sampling instant (which is denoted as $\hat{k}$) after t_k can be chosen as

$$\hat{k} = \begin{cases} a_1, & \tilde{k} = a_1, \\ a_2, & \tilde{k} \in (a_1, a_2], \\ t_k + d_2, & \tilde{k} \geq t_k + d_2, \end{cases}\tag{2}$$

where $a_1 = t_k + d_1 + p(d_2 - d_1)/l$, $a_2 = t_k + d_1 + (p+1)(d_2 - d_1)/l$, $p = 0, 1, \dots, (l-1)$. Then,

$$h_k = d_1 + \frac{b(d_2 - d_1)}{l}, \quad b = 0, 1, \dots, l;\tag{3}$$

that is, the sampling period h_k switches in the finite set $\mathcal{H} = \{d_1, d_1 + (d_2 - d_1)/l, \dots, d_2\}$. If $\tau_k > d_2$, the latest available measurement output will be used by the FDF, and y_k will not be used even if it reaches the FDF eventually.

For a large enough l and during the interval $[t_k, \hat{k})$, one can find that the measurement output adopted by the FDF is approximately y_{k-i_k} , where $i_k = i_m, i_m + 1, \dots$, and i_M , while $i_M - 1$ is the maximum number of consecutive packet

dropouts, $i_m \geq 0$, $i_M > 0$, and $i_m < i_M$. Then the discretized representation of (1) can be described as

$$\begin{aligned} x_{k+1} &= \Phi_k x_k + \Gamma_{1k} u_k + \Gamma_{2k} \omega_k + \Gamma_{3k} f_k, \\ y_k &= C x_k, \end{aligned} \quad (4)$$

where $\Phi_k = e^{Ah_k}$, $\Gamma_{1k} = \int_0^{h_k} e^{As} ds B$, $\Gamma_{2k} = \int_0^{h_k} e^{As} ds B_\omega$, and $\Gamma_{3k} = \int_0^{h_k} e^{As} ds E_f$.

At the k th sampling instant, define the measurement output received by the FDF as $\bar{y}_k$. Then one has $\bar{y}_k = C x_{k-i_k}$. Based on the above statement, one can see that the fault detection filter can be described as

$$\begin{aligned} \hat{x}_{k+1} &= A_f \hat{x}_k + B_f \bar{y}_k, \\ r_k &= C_f \hat{x}_k, \end{aligned} \quad (5)$$

where $\hat{x}_k \in \mathbb{R}^{n_f}$ and $r_k \in \mathbb{R}^q$ are the state of the fault detection filter and the residual signal, respectively; A_f , B_f , and C_f are to be determined.

A reference residual model is usually needed to describe the desired behavior of the residual signal r_k . Introduce the following reference residual model, see also [28] for details:

$$\begin{aligned} \bar{x}_{k+1} &= A_W \bar{x}_k + B_W f_k, \\ \bar{f}_k &= C_W \bar{x}_k + D_W f_k, \end{aligned} \quad (6)$$

where $\bar{x}_k \in \mathbb{R}^{n_w}$ and $\bar{f}_k \in \mathbb{R}^q$ are the state and the output of the reference residual model, respectively; A_W , B_W , C_W , and D_W are known constant matrices of appropriate dimensions.

Define $\xi_k = [x_k^T \ \bar{x}_k^T \ \hat{x}_k^T]^T$, $\nu_k = [u_k^T \ \omega_k^T \ f_k^T]^T$, and $e_k = r_k - \bar{f}_k$. Then, one has

$$\begin{aligned} \xi_{k+1} &= \phi_{1\xi,k} \xi_k + \phi_{2\xi} \xi_{k-i_k} + \phi_{3\xi,k} \nu_k, \\ e_k &= \phi_{1e} \xi_k + \phi_{2e} \nu_k, \end{aligned} \quad (7)$$

where

$$\begin{aligned} \phi_{1\xi,k} &= \begin{bmatrix} \bar{\Phi}_k & 0 \\ 0 & A_f \end{bmatrix}, & \phi_{2\xi} &= \begin{bmatrix} 0 & 0 \\ B_f \bar{C} & 0 \end{bmatrix}, \\ \phi_{3\xi,k} &= \begin{bmatrix} \bar{\Gamma}_k \\ 0 \end{bmatrix}, & \phi_{1e} &= [\bar{C}_W \ C_f], \\ \phi_{2e} &= [0 \ 0 \ -D_W], \\ \bar{\Phi}_k &= \begin{bmatrix} \Phi_k & 0 \\ 0 & A_W \end{bmatrix}, & \bar{C} &= [C \ 0], \\ \bar{\Gamma}_k &= \begin{bmatrix} \Gamma_{1k} & \Gamma_{2k} & \Gamma_{3k} \\ 0 & 0 & B_\omega \end{bmatrix}, & \bar{C}_W &= [0 \ -C_W]. \end{aligned} \quad (8)$$

Remark 1. Generally speaking, the shorter the sampling period in NCSs, the better the system performance. However, a short sampling period will increase the possibility of network congestion. In the closed-loop system (7), the active-varying sampling period method is introduced to make full use of the network bandwidth, which will guarantee the system performance and avoid the occurrence of network congestion simultaneously.

If a constant sampling period h is adopted, one can choose $h = d_2$ to avoid network congestion. In the case of adopting the constant sampling period d_2 , the system in (7) reduces to

$$\begin{aligned} \xi_{k+1} &= \phi_{1\xi} \xi_k + \phi_{2\xi} \xi_{k-i_k} + \phi_{3\xi} \nu_k, \\ e_k &= \phi_{1e} \xi_k + \phi_{2e} \nu_k, \end{aligned} \quad (9)$$

where $\phi_{1\xi} = \begin{bmatrix} \bar{\Phi} & 0 \\ 0 & A_f \end{bmatrix}$, $\phi_{3\xi} = \begin{bmatrix} \bar{\Gamma} \\ 0 \end{bmatrix}$ with $\bar{\Phi} = \begin{bmatrix} \Phi & 0 \\ 0 & A_W \end{bmatrix}$, $\bar{\Gamma} = \begin{bmatrix} \Gamma_1 & \Gamma_2 & \Gamma_3 \\ 0 & 0 & B_\omega \end{bmatrix}$, and $\Phi = e^{Ad_2}$, $\Gamma_1 = \int_0^{d_2} e^{As} ds B$, $\Gamma_2 = \int_0^{d_2} e^{As} ds B_\omega$, $\Gamma_3 = \int_0^{d_2} e^{As} ds E_f$, while $\phi_{2\xi}$, ϕ_{1e} , and ϕ_{2e} are the same as the corresponding items in (7).

To detect the occurrence of faults in time, one should construct a residual evaluation function. If the value of the residual evaluation function is larger than a given threshold, an alarm of faults will be generated. Define the residual evaluation function as

$$\|r\|_T \triangleq \frac{1}{T} \sqrt{\sum_{k=t_1}^{t_2} r_k^T r_k}, \quad T = t_2 - t_1 + 1. \quad (10)$$

Choose a threshold J_{th} as follows:

$$J_{th} = \sup_{\nu_k \in L_2, f_k=0} \|r\|_T. \quad (11)$$

The fault detection logic is

$$\begin{aligned} \|r\|_T &> J_{th}, & \text{with faults,} \\ \|r\|_T &\leq J_{th}, & \text{without faults.} \end{aligned} \quad (12)$$

For the purpose of making full use of the mutually exclusive distribution characteristic of packet dropouts and network-induced delays, one can introduce a scalar ρ_k , and

$$\rho_k = \begin{cases} 1, & i_m \leq i_k \leq \bar{i}, \\ 0, & \bar{i} < i_k \leq i_M, \end{cases} \quad (13)$$

where i_m , $\bar{i}$, and i_M are defined in Section 1.

Based on the established model and the fault detection logic, this paper is concerned with the problem of fault detection filter design for NCSs considering the active-varying sampling periods. The mutually exclusive distribution characteristic of packet dropouts and network-induced delays is made full use of to derive a less conservative fault detection filter design criterion.

3. Fault Detection Filter Design for Active-Varying Sampling-Based NCSs

This section is concerned with fault detection filter design for NCSs considering the active-varying sampling periods. For this purpose, define $\Theta_k = [\xi_k^T \ \xi_{k-1}^T \ \cdots \ \xi_{k-i_M}^T]^T$, and choose the following Lyapunov functional:

$$V_k(\Theta_k) = \sum_{j=1}^4 V_{kj}(\Theta_k), \quad (14)$$

where

$$\begin{aligned}
 V_{k1}(\Theta_k) &= \xi_k^T P \xi_k, \\
 V_{k2}(\Theta_k) &= \sum_{j=k-i_k}^{k-1} \xi_j^T Q \xi_j + \sum_{\ell=-i_M+1}^{-i_m} \sum_{j=k+\ell}^{k-1} \xi_j^T Q \xi_j, \\
 V_{k3}(\Theta_k) &= \sum_{j=k-i_m}^{k-1} \xi_j^T R_1 \xi_j + \sum_{j=k-i_M}^{k-1} \xi_j^T R_2 \xi_j, \\
 V_{k4}(\Theta_k) &= (i_M - i_m) \sum_{\ell=-i_M}^{-i_m-1} \sum_{j=k+\ell}^{k-1} \eta_j^T Z \eta_j,
 \end{aligned} \tag{15}$$

P, Q, R_1, R_2 , and Z are symmetric positive definite matrices, and $\eta_j = \xi_{j+1} - \xi_j$.

Then we state and establish the following result.

Theorem 2. For given scalars $i_m \geq 0$, $i_M > 0$, and $\gamma > 0$, if there exist symmetric positive definite matrices $P_{11}, P_{22}, Q_{11}, Q_{22}, R_{1,11}, R_{1,22}, R_{2,11}, R_{2,22}, Z_{11}$, and Z_{22} and matrices $\hat{A}, \hat{B}, \hat{C}, X_1, X_2, X_3, P_{12}, Q_{12}, R_{1,12}, R_{2,12}$, and Z_{12} , such that the following inequalities hold for $\rho_k = 1$ or $\rho_k = 0$:

$$\begin{bmatrix} \bar{\Omega} & \bar{\Pi}_{12} \\ * & \bar{\Pi}_{22} \end{bmatrix} < 0, \tag{16}$$

where

$$\bar{\Omega} = \begin{bmatrix} \bar{\Omega}_{11} & 0 & 0 & 0 & 0 \\ * & \bar{\Omega}_{22} & \bar{\Omega}_{23} & 0 & 0 \\ * & * & \bar{\Omega}_{33} & \bar{\Omega}_{34} & 0 \\ * & * & * & \bar{\Omega}_{44} & 0 \\ * & * & * & * & -\gamma I \end{bmatrix},$$

$$\bar{\Pi}_{12} = \begin{bmatrix} H_1 & H_1 - \bar{G} & H_4 \\ 0 & 0 & 0 \\ H_2 & H_2 & 0 \\ 0 & 0 & 0 \\ H_3 & H_3 & \phi_{2e}^T \end{bmatrix},$$

$$\bar{\Pi}_{22} = \text{diag}\{\mathcal{X}_1, \mathcal{X}_2, -\gamma I\},$$

$$\bar{\Omega}_{11} = -\bar{P} + (i_M - i_m + 1)\bar{Q} + \bar{R}_1 + \bar{R}_2,$$

$$\bar{\Omega}_{22} = -(1 - \rho_k)\bar{Q} - \bar{R}_1 - \left(1 + \rho_k \frac{i_M - \bar{i}}{\bar{i} - i_m}\right)\bar{Z},$$

$$\bar{\Omega}_{23} = \left(1 + \rho_k \frac{i_M - \bar{i}}{\bar{i} - i_m}\right)\bar{Z},$$

$$\bar{\Omega}_{33} = -\bar{Q} - 2\bar{Z} - \left(\rho_k \frac{i_M - \bar{i}}{\bar{i} - i_m} + (1 - \rho_k) \frac{\bar{i} - i_m}{i_M - \bar{i}}\right)\bar{Z},$$

$$\bar{\Omega}_{34} = \left(1 + (1 - \rho_k) \frac{\bar{i} - i_m}{i_M - \bar{i}}\right)\bar{Z},$$

$$\bar{\Omega}_{44} = -\bar{R}_2 - \left(1 + (1 - \rho_k) \frac{\bar{i} - i_m}{i_M - \bar{i}}\right)\bar{Z},$$

$$H_1 = \begin{bmatrix} \bar{\Phi}_k^T X_1 & \bar{\Phi}_k^T X_2 \\ \hat{A} & \hat{A} \end{bmatrix}, \quad H_2 = \begin{bmatrix} \bar{C}^T \hat{B} & \bar{C}^T \hat{B} \\ 0 & 0 \end{bmatrix},$$

$$H_3 = [\bar{\Gamma}_k^T X_1 \quad \bar{\Gamma}_k^T X_2], \quad H_4 = \begin{bmatrix} \bar{C}_W^T \\ \bar{C} \end{bmatrix},$$

$$\mathcal{X}_1 = \bar{P} - \bar{G} - \bar{G}^T,$$

$$\mathcal{X}_2 = (i_M - i_m)^{-2} (\bar{Z} - \bar{G} - \bar{G}^T),$$

$$\bar{P} = \begin{bmatrix} P_{11} & P_{12} \\ * & P_{22} \end{bmatrix}, \quad \bar{Q} = \begin{bmatrix} Q_{11} & Q_{12} \\ * & Q_{22} \end{bmatrix},$$

$$\bar{R}_1 = \begin{bmatrix} R_{1,11} & R_{1,12} \\ * & R_{1,22} \end{bmatrix}, \quad \bar{R}_2 = \begin{bmatrix} R_{2,11} & R_{2,12} \\ * & R_{2,22} \end{bmatrix},$$

$$\bar{Z} = \begin{bmatrix} Z_{11} & Z_{12} \\ * & Z_{22} \end{bmatrix}, \quad \bar{G} = \begin{bmatrix} X_1 & X_2 \\ X_3 & X_3 \end{bmatrix}, \tag{17}$$

then under the fault detection filter (5) with

$$A_f = G_3^{-T} \bar{A}^T G_3^{-1} G_4,$$

$$B_f = G_3^{-T} \bar{B}^T, \tag{18}$$

$$C_f = \bar{C}^T G_3^{-1} G_4,$$

the residual system (7) is asymptotically stable with an H_∞ norm bound γ .

Proof. Taking the time difference of the Lyapunov functional $V_k(\Theta_k)$ in (14) along the trajectory of the system (7), one has

$$\begin{aligned}
 \Delta V_k(\Theta_k) &= V_{k+1}(\Theta_{k+1}) - V_k(\Theta_k) \\
 &= \sum_{j=1}^4 \Delta V_{kj}(\Theta_k),
 \end{aligned} \tag{19}$$

where

$$\Delta V_{k1}(\Theta_k) = \xi_{k+1}^T P \xi_{k+1} - \xi_k^T P \xi_k,$$

$$\begin{aligned}
 \Delta V_{k2}(\Theta_k) &= (i_M - i_m + 1) \xi_k^T Q \xi_k \\
 &+ \sum_{j=k-i_m+1}^{k-1} \xi_j^T Q \xi_j - \sum_{j=k-i_k+1}^{k-1} \xi_j^T Q \xi_j \\
 &+ \sum_{j=k-i_{k+1}+1}^{k-i_m} \xi_j^T Q \xi_j \\
 &- \sum_{j=k-i_M+1}^{k-i_m} \xi_j^T Q \xi_j - \xi_{k-i_k}^T Q \xi_{k-i_k}.
 \end{aligned} \tag{20}$$

Notice that $\sum_{j=k-i_{k+1}+1}^{k-i_m} \xi_j^T Q \xi_j - \sum_{j=k-i_M+1}^{k-i_m} \xi_j^T Q \xi_j \leq 0$. Considering the mutually exclusive distribution characteristic of i_k , one has

$$\sum_{j=k-i_m+1}^{k-1} \xi_j^T Q \xi_j - \sum_{j=k-i_k+1}^{k-1} \xi_j^T Q \xi_j \leq -(1-\rho_k) \xi_{k-i_m}^T Q \xi_{k-i_m}. \quad (21)$$

Then,

$$\Delta V_{k2}(\Theta_k) \leq (i_M - i_m + 1) \xi_k^T Q \xi_k - \xi_{k-i_k}^T Q \xi_{k-i_k} \\ - (1-\rho_k) \xi_{k-i_m}^T Q \xi_{k-i_m},$$

$$\Delta V_{k3}(\Theta_k) = \xi_k^T (R_1 + R_2) \xi_k - \xi_{k-i_m}^T R_1 \xi_{k-i_m} - \xi_{k-i_M}^T R_2 \xi_{k-i_M}. \quad (22)$$

Adopting the mutually exclusive distribution characteristic of i_k and the Jensen integral inequality in [29], one has

$$\Delta V_{k4}(\Theta_k) = (i_M - i_m)^2 (\xi_{k+1} - \xi_k)^T Z (\xi_{k+1} - \xi_k) \\ - (i_M - i_m) \sum_{j=k-i_m}^{k-i_M-1} \eta_j^T Z \eta_j \\ \leq (i_M - i_m)^2 (\xi_{k+1} - \xi_k)^T Z (\xi_{k+1} - \xi_k) \\ - \rho_k \frac{i_M - \bar{i}}{\bar{i} - i_m} \varphi_{1k}^T Z \varphi_{1k} \\ - \varphi_{1k}^T Z \varphi_{1k} - \varphi_{2k}^T Z \varphi_{2k} \\ - (1-\rho_k) \frac{\bar{i} - i_m}{i_M - \bar{i}} \varphi_{2k}^T Z \varphi_{2k} \quad (23)$$

and $\varphi_{1k} = \xi_{k-i_m} - \xi_{k-i_k}$, $\varphi_{2k} = \xi_{k-i_k} - \xi_{k-i_M}$.

Then, by combining (7) and (20)–(23) together, one has

$$\Delta V_k(\Theta_k) + \gamma^{-1} e_k^T e_k - \gamma \nu_k^T \nu_k \leq \tilde{\xi}_k^T (\Omega + \Xi) \tilde{\xi}_k, \quad (24)$$

where $\tilde{\xi}_k = [\xi_k^T \ \xi_{k-i_m}^T \ \xi_{k-i_k}^T \ \xi_{k-i_M}^T \ \nu_k^T]^T$ and

$$\Omega = \begin{bmatrix} \Omega_{11} & 0 & 0 & 0 & 0 \\ * & \Omega_{22} & \Omega_{23} & 0 & 0 \\ * & * & \Omega_{33} & \Omega_{34} & 0 \\ * & * & * & \Omega_{44} & 0 \\ * & * & * & * & -\gamma I \end{bmatrix} \quad (25)$$

with

$$\Omega_{11} = -P + (i_M - i_m + 1)Q + R_1 + R_2,$$

$$\Omega_{22} = -(1-\rho_k)Q - R_1 - \left(1 + \rho_k \frac{i_M - \bar{i}}{\bar{i} - i_m}\right)Z,$$

$$\Omega_{23} = \left(1 + \rho_k \frac{i_M - \bar{i}}{\bar{i} - i_m}\right)Z,$$

$$\Omega_{33} = -Q - 2Z - \left(\rho_k \frac{i_M - \bar{i}}{\bar{i} - i_m} + (1-\rho_k) \frac{\bar{i} - i_m}{i_M - \bar{i}}\right)Z,$$

$$\Omega_{34} = \left(1 + (1-\rho_k) \frac{\bar{i} - i_m}{i_M - \bar{i}}\right)Z,$$

$$\Omega_{44} = -R_2 - \left(1 + (1-\rho_k) \frac{\bar{i} - i_m}{i_M - \bar{i}}\right)Z,$$

$$\Xi = Y_1^T P Y_1 + (i_M - i_m)^2 Y_2^T Z Y_2 + \gamma^{-1} Y_3^T Y_3,$$

$$Y_1 = [\phi_{1\xi,k} \ 0 \ \phi_{2\xi} \ 0 \ \phi_{3\xi,k}],$$

$$Y_2 = [(\phi_{1\xi,k} - I) \ 0 \ \phi_{2\xi} \ 0 \ \phi_{3\xi,k}],$$

$$Y_3 = [\phi_{1e} \ 0 \ 0 \ 0 \ \phi_{2e}].$$

(26)

From (24), one can see that if $\Omega + \Xi < 0$, then $\Delta V_k(\Theta_k) + \gamma^{-1} e_k^T e_k - \gamma \nu_k^T \nu_k < 0$. By using Schur complement, $\Omega + \Xi < 0$ is equivalent to

$$\begin{bmatrix} \Omega & \Pi_{12} \\ * & \Pi_{22} \end{bmatrix} < 0, \quad (27)$$

where $\Pi_{12} = [Y_1^T \ Y_2^T \ Y_3^T]$ and $\Pi_{22} = \text{diag}\{-P^{-1}, -(i_M - i_m)^{-2}Z^{-1}, -\gamma I\}$.

Introduce a matrix $G = \begin{bmatrix} G_1 & G_2 \\ G_3 & G_4 \end{bmatrix}$, where the selection of G_3 and G_4 is discussed in Remark 3. Pre- and postmultiplying both sides of (27) with $\text{diag}\{I, \dots, I, G^T, G^T, I\}$ and its

transpose, and considering that $Z - G - G^T \geq -G^T Z^{-1} G$ and $P - G - G^T \geq -G^T P^{-1} G$, one can see that if the inequalities in (28) are satisfied for $\rho_k = 1$ or $\rho_k = 0$, the inequalities in (27) are also satisfied as follows:

$$\begin{bmatrix} \Omega & \bar{\Pi}_{12} \\ * & \bar{\Pi}_{22} \end{bmatrix} < 0, \quad (28)$$

where

$$\bar{\Pi}_{12} = [Y_1^T G \ Y_2^T G \ Y_3^T],$$

$$\bar{\Pi}_{22}$$

$$= \text{diag}\{P - G - G^T, (i_M - i_m)^{-2}(Z - G - G^T), -\gamma I\}. \quad (29)$$

Suppose that $M = \text{diag}\{I, G_4^{-1}G_3\}$. Pre- and postmultiplying both sides of (28) with $\text{diag}\{\underbrace{M^T, \dots, M^T}_4, I, M^T, M^T, I\}$ and

its transpose and defining $M^T G M = \bar{G} = \begin{bmatrix} X_1 & X_2 \\ X_3 & X_3 \end{bmatrix}$, $G_1 = X_1$, $G_2 G_4^{-1} G_3 = X_2$, $G_3^T G_4^{-T} G_3 = X_3$, $M^T P M = \bar{P} = \begin{bmatrix} P_{11} & P_{12} \\ * & P_{22} \end{bmatrix}$, $M^T Q M = \bar{Q} = \begin{bmatrix} Q_{11} & Q_{12} \\ * & Q_{22} \end{bmatrix}$, $M^T R_1 M = \bar{R}_1 = \begin{bmatrix} R_{1,11} & R_{1,12} \\ * & R_{1,22} \end{bmatrix}$, $M^T R_2 M = \bar{R}_2 = \begin{bmatrix} R_{2,11} & R_{2,12} \\ * & R_{2,22} \end{bmatrix}$, $M^T Z M = \bar{Z} = \begin{bmatrix} Z_{11} & Z_{12} \\ * & Z_{22} \end{bmatrix}$, $G_3^T G_4^{-T} A_f^T G_3 = \bar{A}$, $B_f^T G_3 = \bar{B}$, $G_3^T G_4^{-T} C_f^T = \bar{C}$, one can see that the inequalities in (28) are equivalent to the ones in (16).

Then, by using the definition of H_∞ performance, one can see that if the inequalities in (16) are satisfied for $\rho_k = 1$ or $\rho_k = 0$, the system (7) is asymptotically stable with an H_∞ norm bound γ . This completes the proof. $\square$

Remark 3. Notice that the feasibility of the inequalities in (16) implies the nonsingularity of $\widehat{G}$ and X_3 . Since $X_3 = G_3^T G_4^{-T} G_3$, the nonsingularity of X_3 implies that G_3 and G_4 are also nonsingular. By using the singular value decomposition of X_3^T , one can obtain the matrices G_3^T and $G_4^{-1} G_3$.

It should be pointed out that the active-varying sampling period method is adopted in Theorem 2 to deal with fault detection filter design. Even if the constant sampling period is adopted, the fault detection filter design in Theorem 2 is still applicable. For the purpose of comparison, we establish the following fault detection filter design criterion for the system (9) with a constant sampling period.

Corollary 4. For given scalars $i_m \geq 0$, $i_M > 0$, and $\gamma > 0$, if there exist symmetric positive definite matrices P_{11} , P_{22} , Q_{11} , Q_{22} , $R_{1,11}$, $R_{1,22}$, $R_{2,11}$, $R_{2,22}$, Z_{11} , and Z_{22} and matrices $\widehat{A}$, $\widehat{B}$, $\widehat{C}$, X_1 , X_2 , X_3 , P_{12} , Q_{12} , $R_{1,12}$, $R_{2,12}$, and Z_{12} , such that the following inequalities hold for $\rho_k = 1$ or $\rho_k = 0$:

$$\begin{bmatrix} \widetilde{\Omega} & \widehat{\Pi}_{12} \\ * & \widehat{\Pi}_{22} \end{bmatrix} < 0, \quad (30)$$

where $\widetilde{\Omega}$ and $\widehat{\Pi}_{22}$ are the same as the corresponding items in (16), $\widehat{\Pi}_{12}$ is derived from $\widetilde{\Pi}_{12}$ in (16) by substituting $\widehat{\Phi}_k$ and $\widehat{\Gamma}_k$ with $\widehat{\Phi}$ and $\widehat{\Gamma}$, respectively, and $\widehat{\Phi}$ and $\widehat{\Gamma}$ are the same as the corresponding items in (9), then, under the fault detection filter (5) with

$$\begin{aligned} A_f &= G_3^{-T} \widehat{A}^T G_3^{-1} G_4, \\ B_f &= G_3^{-T} \widehat{B}^T, \\ C_f &= \widehat{C}^T G_3^{-1} G_4, \end{aligned} \quad (31)$$

the residual system (9) is asymptotically stable with an H_∞ norm bound γ .

In the following, we will analyze the merits for considering the mutually exclusive distribution characteristic of packet dropouts and network-induced delays.

If the mutually exclusive distribution characteristic of packet dropouts and network-induced delays is neglected, the result in Theorem 2 is described as shown in the following corollary.

Corollary 5. For given scalars $i_m \geq 0$, $i_M > 0$, and $\gamma > 0$, if there exist symmetric positive definite matrices P_{11} , P_{22} , Q_{11} , Q_{22} , $R_{1,11}$, $R_{1,22}$, $R_{2,11}$, $R_{2,22}$, Z_{11} , and Z_{22} and matrices $\widehat{A}$, $\widehat{B}$, $\widehat{C}$, X_1 , X_2 , X_3 , P_{12} , Q_{12} , $R_{1,12}$, $R_{2,12}$, and Z_{12} , such that

$$\begin{bmatrix} \widetilde{\Omega} & \widetilde{\Pi}_{12} \\ * & \widetilde{\Pi}_{22} \end{bmatrix} < 0, \quad (32)$$

where $\widetilde{\Omega}$ is derived from $\widetilde{\Omega}$ in (16) by deleting all the items multiplied by ρ_k and $(1 - \rho_k)$, $\widetilde{\Pi}_{12}$ and $\widetilde{\Pi}_{22}$ are the same as the corresponding items in (16), then, under the fault detection filter (5) with

$$\begin{aligned} A_f &= G_3^{-T} \widehat{A}^T G_3^{-1} G_4, \\ B_f &= G_3^{-T} \widehat{B}^T, \\ C_f &= \widehat{C}^T G_3^{-1} G_4, \end{aligned} \quad (33)$$

the residual system (7) is asymptotically stable with an H_∞ norm bound γ .

The following theorem establishes the relationship between Theorem 2 and Corollary 5.

Theorem 6. Consider the system (7). If the fault detection filter design criterion presented in Corollary 5 is satisfied, then the fault detection filter design criterion in Theorem 2 is also satisfied.

Proof. Define the matrices $\begin{bmatrix} \widetilde{\Omega} & \widetilde{\Pi}_{12} \\ * & \widetilde{\Pi}_{22} \end{bmatrix}$ in (16) and $\begin{bmatrix} \widetilde{\Omega} & \widetilde{\Pi}_{12} \\ * & \widetilde{\Pi}_{22} \end{bmatrix}$ in (32) as N and $\widetilde{N}$, respectively. Then,

$$\begin{aligned} N &= \widetilde{N} - \text{diag} \left\{ 0, (1 - \rho_k) \widetilde{Q}, \underbrace{0, \dots, 0}_6 \right\} \\ &\quad - \rho_k \frac{i_M - \bar{i}}{\bar{i} - i_m} \Upsilon_4^T \widetilde{Z} \Upsilon_4 \\ &\quad - (1 - \rho_k) \frac{\bar{i} - i_m}{i_M - \bar{i}} \Upsilon_5^T \widetilde{Z} \Upsilon_5, \end{aligned} \quad (34)$$

where $\Upsilon_4 = \begin{bmatrix} 0 & I & -I & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$ and $\Upsilon_5 = \begin{bmatrix} 0 & 0 & I & -I & 0 & 0 & 0 & 0 \end{bmatrix}$. From (34), one can see that if $\widetilde{N} < 0$ is satisfied, $N < 0$ is also satisfied. This completes the proof. $\square$

Remark 7. It has been proved theoretically that the fault detection filter design criterion in Theorem 2 is easier to be satisfied than the fault detection filter design criterion in Corollary 5, which illustrates the merits for considering the mutually exclusive distribution characteristic of packet dropouts and network-induced delays. Notice that the mutually exclusive distribution characteristic of packet dropouts and network-induced delays is adopted to deal with bounding inequalities for products of vectors. Even for the systems in [30, 31] without considering the occurrence of faults, adopting the mutually exclusive distribution characteristic of packet dropouts and network-induced delays will also introduce better results. The corresponding results are omitted here for brevity.

In the following, we will show the effectiveness of the proposed fault detection filter design by the simulation results.

4. Simulation Results and Discussion

To illustrate the effectiveness of the proposed fault detection filter design, we consider the following linear model for the motion of ships, see also [32–34] for similar models:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) + B_\omega\omega(t) + E_f f(t), \\ y(t) &= Cx(t),\end{aligned}\quad (35)$$

where $x(t) = [z_\delta(t) \ \dot{z}_\delta(t) \ \theta_\delta(t) \ \dot{\theta}_\delta(t)]^T$ is the state vector, $u(t) = [a_{1\delta}(t) \ a_{2\delta}(t)]^T$ is the control input vector, $\omega(t) = [\omega'_1(t) \ \omega'_2(t)]^T$ is the unknown disturbance input, and $f(t)$ is the fault signal. The physical meaning for $z_\delta(t)$, $\dot{z}_\delta(t)$, $\theta_\delta(t)$, $\dot{\theta}_\delta(t)$, $a_{1\delta}(t)$, and $a_{2\delta}(t)$ can be found in [34] and the references therein.

The system matrices in (35) are similar to the ones in [34] with

$$\begin{aligned}A &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ -0.1923 & -14.3338 & -210.7117 & -87.9924 \\ 0 & 0 & 0 & 1 \\ -0.0002 & -0.015 & -0.2210 & -9.9805 \end{bmatrix}, \\ B &= \begin{bmatrix} 0 & 0 \\ -30.0785 & -37.0679 \\ 0 & 0 \\ 1.3379 & -2.3439 \end{bmatrix}, \\ B_w &= \begin{bmatrix} 0 & 0 \\ 18.7186 & -0.0636 \\ 0 & 0 \\ 0.5736 & -0.0006 \end{bmatrix}, \\ E_f &= -B \times \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad C = [0 \ 1 \ 0 \ 1].\end{aligned}\quad (36)$$

The parameters for the fault weighting system (6) are chosen as $A_W = 0.8$, $B_W = 0.2$, $C_W = 0.9$, and $D_W = -0.6$. The active-varying sampling periods are considered in this paper, and suppose that the sampling periods switch in the finite set $\theta = \{0.05 \text{ s}, 0.1 \text{ s}\}$, $i_m = 1$, $i_M = 3$. Then one has $\bar{i} = 2$. Define $I_2 = [0 \ 1 \ 0 \ 0 \ 0]^T$ and $I_4 = [0 \ 0 \ 0 \ 1 \ 0]^T$. To avoid that some elements of the obtained matrix B_f are close to zero, we assume that $\hat{B}I_2 + I_2^T \hat{B}^T + 0.1 < 0$, $\hat{B}I_4 + I_4^T \hat{B}^T + 0.1 < 0$. Discretizing the system (35), constructing the closed-loop system, and solving the fault detection filter design criterion presented in Theorem 2, one has

$$A_f = \begin{bmatrix} 0.7845 & 0.0189 & -0.1688 & 0.0102 & -0.0001 \\ 0.0033 & 0.3841 & 0.0737 & 0.0450 & -0.0001 \\ -0.0307 & 0.0408 & 0.4627 & 0.0350 & 0.0007 \\ 0.0036 & 0.0472 & 0.0351 & 0.9927 & -0.0001 \\ 0.0001 & -0.0001 & 0.0009 & -0.0000 & 1.0000 \end{bmatrix},$$

FIGURE 1: Residual evaluation function response $\|r\|_T$ for $h_k = h_1$.

$$B_f = \begin{bmatrix} 0.0156 \\ 0.0233 \\ 0.0045 \\ -0.0023 \\ -0.0000 \end{bmatrix},$$

$$C_f = [-0.0127 \ 0.0020 \ 0.0170 \ -0.0035 \ -0.0002]. \quad (37)$$

Suppose that the initial state of the augmented closed-loop system (7) is $\xi_0 = [0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]^T$. For $0 \leq k < 1000$, i_k will switch between 1 and 2 in cycles. For $0 \leq k < 99$ and $402 \leq k < 1000$, u_k , ω_k , and f_k are assumed to be zero. For $100 \leq k < 402$, suppose that $u_k = [0.1 \ 0.1]^T$, $\omega_k = [0.1 \sin(k) \ 0.1 \sin(k)]^T$, and in the case that a fault occurs, suppose that $f_k = 2$, where u_k , ω_k , and f_k denote the values of $u(t)$, $\omega(t)$, and $f(t)$ at the k th sampling instant, respectively.

It should be pointed out that the fault detection filter design method in Theorem 2 is applicable for $h_k = h_1$, switched sampling periods (i.e., h_k switches between h_1 and h_2 in cycles), and $h_k = h_2$. The residual evaluation function response $\|r\|_T$ for $h_k = h_1$, switched sampling periods, and $h_k = h_2$ is presented in Figures 1, 2, and 3, respectively. Considering the fault detection logic presented in (12) and from Figures 1, 2, and 3, one can see that the newly proposed fault detection scheme can not only reflect the occurrence of faults in time but also recognize the faults without confusing faults with the disturbance ω_k .

Define n as the number of needed sampling periods for fault detection. Table 1 shows the numbers of needed sampling periods for fault detection corresponding to different

FIGURE 2: Residual evaluation function response $\|r\|_T$ for switched sampling periods.

FIGURE 3: Residual evaluation function response $\|r\|_T$ for $h_k = h_2$.

cases. As one can see in Table 1, the shorter the sampling period, the smaller the number of needed sampling periods for fault detection, which illustrates the effectiveness of the newly proposed active-varying sampling-based fault detection scheme.

5. Conclusions

The fault detection filter design for continuous-time NCSs considering packet dropouts and network-induced delays

TABLE 1: The numbers of the needed sampling periods for fault detection.

Method	$h_k = h_1$	$h_k = h_1$ or $h_k = h_2$	$h_k = h_2$
n	10	11	12

has been studied in this paper. The active-varying sampling period method has been introduced to establish a new discretized model and improve the fault detection performance for the considered NCSs. The fault detection filter design criterion which considers the mutually exclusive distribution characteristic of packet dropouts and network-induced delays has been proved theoretically to be less conservative than the criterion without considering such a mutually exclusive distribution characteristic. The merits and effectiveness of the proposed active-varying sampling-based fault detection filter design have been verified by the simulation results.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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