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Research article

Event-triggered decentralized adaptive fault-tolerant control of uncertain interconnected nonlinear systems with actuator failures

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ABSTRACT

This paper investigates the event-triggered decentralized adaptive tracking problem of a class of uncertain interconnected nonlinear systems with unexpected actuator failures. It is assumed that local control signals are transmitted to local actuators with time-varying faults whenever predefined conditions for triggering events are satisfied. Compared with the existing control-input-based event-triggering strategy for adaptive control of uncertain nonlinear systems, the aim of this paper is to propose a tracking-error-based event-triggering strategy in the decentralized adaptive fault-tolerant tracking framework. The proposed approach can relax drastic changes in control inputs caused by actuator faults in the existing triggering strategy. The stability of the proposed event-triggering control system is analyzed in the Lyapunov sense. Finally, simulation comparisons of the proposed and existing approaches are provided to show the effectiveness of the proposed theoretical result in the presence of actuator faults.

1. Introduction

Owing to limited resources in practical network control systems, many research efforts have focused on the event-triggered control field. The event-triggered control designs for linear systems [1,2] have recently been extended to nonlinear systems [3–6]. These approaches for nonlinear systems [3–6] commonly assume that nonlinear functions are exactly known under the input-to-state stability (ISS) condition and satisfy the global Lipschitz condition. To relax these assumptions, an adaptive event-triggered control scheme for lower-triangular nonlinear systems with actuator failures and parametric uncertainties was developed in Ref. [7], without assuming the ISS condition, where the relative triggering threshold was related to the magnitude of the control signal. It is well known that the dynamic behavior of the control signal is provided in the procedure for accommodating actuator faults with a time-varying bias type [8,9]. Thus, the control-input-based triggering strategy [7] may cause drastic changes in the triggering threshold and the event-triggered control signal after the actuator failures occur, which leads to an increase in the control costs. In this paper, we would like to provide a positive solution to this problem in the presence of actuator failures.

Fault-tolerant control methods for nonlinear systems have been developed in the control industry to increase the safety and reliability of control systems in the presence of unexpected faults [10–15]. In Refs. [8,16,17], the adaptive actuator failure compensation problems were addressed for strict-feedback nonlinear systems where the recursive and systematic design techniques [18,19] were employed to design fault-tolerant controllers. The adaptive fault-tolerant control approaches were proposed in the presence of unknown strict-feedback nonlinearities [20]. These research results have been extended to decentralized adaptive fault-tolerant control problems of nonlinear interconnected systems with unexpected actuator failures and unknown parameters [21–25]. To deal with the decentralized control problem in the presence of limited network resources, the event-triggered decentralized control approaches have been studied for interconnected linear systems [26–29] and for interconnected nonlinear systems [30–33]. However, these results [30–33] for interconnected nonlinear systems have the following two restrictions: (R1) nonlinearities should be known under the ISS assumption, and thus, the results cannot be applied to systems with uncertain nonlinear interactions unmatched in the control input; and (R2) the effects of the actuator failures are not considered in the decentralized event-triggering control field. To the best of our knowledge, the design problem of event-triggered decentralized control schemes for uncertain interconnected nonlinear systems is still open.

The objective of this paper is to propose a tracking-error-based event-triggered strategy for the decentralized adaptive fault-tolerant tracking of uncertain interconnected strict-feedback nonlinear sys-

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tems with unexpected actuator faults. Our primary contributions lie in deriving the event-triggering threshold dependent on the tracking error, rather than the control input sensitive to time-varying actuator failures, in the Lyapunov sense. In addition, the decentralization of the proposed event-triggering threshold is considered, namely, the local tracking error is only used for designing the event-triggering condition of each subsystem. It is shown that all the signals in the total closed-loop system are semi-globally ultimately uniformly bounded, and the tracking errors converge to a neighborhood of the origin.

The main contributions of this paper are summarized as follows:

(C1) Different from the existing adaptive event-based control result [7] for uncertain nonlinear systems where the triggering threshold in the controller-to-actuator channel is based on the control signal, we present a new decentralized event-triggering strategy based on the local tracking error in the presence of actuator faults. Thus, undesirable drastic changes between the previously released and newly updated inputs of the local actuator caused after the occurrence of the actuator faults can be relaxed by using the proposed local tracking-error-based triggering threshold.

(C2) Compared with the existing event-triggered decentralized control approaches for interconnected nonlinear systems [30–33], the uncertain nonlinear interactions and actuator faults are considered and the decentralized event-triggering thresholds using local tracking errors are designed in this paper.

This paper is organized as follows. In Section 2, we formulate the control problem. A tracking-error-based event-triggered decentralized adaptive tracking scheme is presented and its stability is analyzed in Section 3. Simulation results are discussed in Section 4. Finally, Section 5 provides some conclusions.

2. Problem formulation

Consider a class of uncertain interconnected nonlinear systems composed of N subsystems with actuator failures described by

$$\begin{aligned} \dot{x}_{i,k} &= g_{i,k}x_{i,k+1} + \theta_{i,k}^{\top} f_{i,k}(\bar{x}_{i,k}) + h_{i,k}(y) + d_{i,k}, \\ \dot{x}_{i,n_i} &= g_{i,n_i}u_i^F + \theta_{i,n_i}^{\top} f_{i,n_i}(x_i) + h_{i,n_i}(y) + d_{i,n_i}, \\ y_i &= x_{i,1}, \end{aligned} \tag{1}$$

where $i = 1,\ldots, N$, $k = 1,\ldots, n_i - 1$, $\bar{x}_{i,k} = [x_{i,1}, \ldots, x_{i,k}]^{\top} \in \mathbb{R}^k$ and $x_i = [x_{i,1}, \ldots, x_{i,n_i}]^{\top} \in \mathbb{R}^{n_i}$ are the state variable vectors of the ith subsystem, $y_i \in \mathbb{R}$ is the system output of the ith subsystem, $y = [y_1, \ldots, y_N]^{\top}$, $f_{i,j}(\cdot) : \mathbb{R}^j \mapsto \mathbb{R}^{q_{i,j}}$, $j = 1,\ldots, n_i$, are known nonlinear function vectors, $g_{i,j} \in \mathbb{R}$ and $\theta_{i,j} \in \mathbb{R}^{q_{i,j}}$ are unknown constants and vectors denoting parametric uncertainties, $d_{i,j}$ are unknown time-varying external disturbances, and $h_{i,j}(\cdot) : \mathbb{R}^N \mapsto \mathbb{R}$ are unknown nonlinear interaction terms among subsystems.

$u_i^F \in \mathbb{R}$ denotes the ith faulty control input with the following fault type [22].

$$u_i^F(t) = \eta_{i,1}(t)u_i(t) + \eta_{i,2}(t) \tag{2}$$

where

$$\eta_{i,1}(t) = \begin{cases} \eta_{i,1,m}(t), & \text{if} \quad t \in [t_{i,m,s}, t_{i,m,e}), \\ 1, & \text{if} \quad t \in [t_{i,m,e}, t_{i,m+1,s}) \text{ or } t \in [0, t_{i,1,s}), \end{cases} \tag{3}$$

$$\eta_{i,2}(t) = \begin{cases} \eta_{i,2,m}(t), & \text{if} \quad t \in [t_{i,m,s}, t_{i,m,e}), \\ 0, & \text{if} \quad t \in [t_{i,m,e}, t_{i,m+1,s}) \text{ or } t \in [0, t_{i,1,s}). \end{cases} \tag{4}$$

Here, $m \in \mathbb{Z}^+$, u_i is the input of the ith local actuator, $\eta_{i,1,m}(t)$ and $\eta_{i,2,m}(t)$ are unknown time-varying fault parameters at the mth failure of the ith local actuator and satisfy $0 < \underline{\eta}_{i,1} \le \eta_{i,1,m}(t) < 1$ and $|\eta_{i,2,m}(t)| \le \bar{\eta}_{i,2}$, respectively, with unknown constants $\underline{\eta}_{i,1}$ and $\bar{\eta}_{i,2}$, $t_{i,m,s}$ and $t_{i,m,e}$ indicate the time instants when the mth failure on the ith actuator starts and ends, respectively. As stated in Ref. [22], the ith local actuator fails from $t_{i,m,s}$ until $t_{i,m,e}$ and if $t_{i,m+1,s} > t_{i,m,e}$, the failed actuator recovers its normal operation from $t_{i,m,e}$ until $t_{i,m+1,s}$ when the next failure takes place, and if $t_{i,m+1,s} = t_{i,m,e}$, the failure form $\eta_{i,1,m}(t)$ becomes $\eta_{i,1,m+1}(t)$ at $t_{i,m,e}$.

Remark 1. System 1 can represent cases in which uncertain nonlinear interaction and actuator faults influence practical nonlinear systems, such as interconnected industrial manipulators, interconnected inverted pendulums, interconnected helicopters, and interconnected electrical power systems (see Refs. [34–40] and the references therein). In general, uncertainties in the interaction terms and faults in the actuators affect the network control system of interconnected mechanical systems.

Assumption 1. The desired signals $y_{i,r}$ and their derivatives $\dot{y}_{i,r}$ and $\ddot{y}_{i,r}$ are bounded where $i = 1, \ldots, N$ and $k = 1, \ldots, n_i$.

Assumption 2. The unknown constants $g_{i,k}$ are non-zero and their signs are known where $i = 1,\ldots, N$ and $k = 1,\ldots, n_i$. Without losing generality, we assume $g_{i,k} > 0$.

Assumption 3. The unknown time-varying external disturbances $d_{i,k}$ are bounded as $|d_{i,k}| \le \bar{d}_{i,k}$ with unknown constants $\bar{d}_{i,k} > 0$ where $i = 1, \ldots, N$ and $k = 1, \ldots, n_i$.

Assumption 4. [41] For the unknown interconnected nonlinearities $h_{i,k}(y)$, it holds that $|h_{i,k}(y)| \le \sum_{j=1}^{N} \rho_{i,k,j}\varpi_{i,k,j}(y_j)$ where $i = 1,\ldots, N$, $k = 1,\ldots, n_i$, $\rho_{i,k,j} > 0$ are unknown constants, and $\varpi_{i,k,j}(y_j) > 0$ are known smooth functions.

Lemma 1. [42] *For any $\varepsilon > 0$ and $z \in \mathbb{R}$, it holds that* $0 \le |z| - z \tanh(z/\varepsilon) \le 0.2785\varepsilon$.

Problem 1. Consider [1] with actuator faults [2]. Our problem is to design decentralized adaptive fault-tolerant control laws u_i and their decentralized event-triggered mechanism using only local tracking errors such that all the signals of the controlled system are bounded and the outputs y_i track the desired signals $y_{i,r}$.

Remark 2. Compared with the existing event-triggered decentralized control results for interconnected nonlinear systems [30–33], this paper considers system uncertainties and actuator faults without using ISS assumptions. Thus, the existing results cannot provide a solution to Problem 1.

3. Event-triggered decentralized adaptive tracking scheme

3.1. Controller design

This section focuses on the design of an event-triggered decentralized adaptive tracking scheme for system [1] in the presence of parametric uncertainties, external disturbances, and actuator faults. The proposed controller design is based on the dynamic surface design [19] using the following coordinate transformation:

$$\begin{cases} z_{i,1} = y_i - y_{i,r}, \\ z_{i,k+1} = x_{i,k+1} - \bar{\alpha}_{i,k}, \end{cases} \tag{5}$$

$$s_{i,k} = \bar{\alpha}_{i,k} - \alpha_{i,k}, \tag{6}$$

where $i = 1,\ldots, N$, $k = 1,\ldots, n_i - 1$, $z_{i,1}$, and $z_{i,k+1}$ are error surfaces, $s_{i,k}$ are boundary layer errors, $\alpha_{i,k}$ are virtual control laws, and $\bar{\alpha}_{i,k}$ are the signals obtained by the first-order low-pass filters $\tau_{i,k}\dot{\bar{\alpha}}_{i,k} + \bar{\alpha}_{i,k} = \alpha_{i,k}$, $\bar{\alpha}_{i,k}(0) = \alpha_{i,k}(0)$, where $\tau_{i,k} > 0$ are time constants.

Step i, 1: Consider the first error surface $z_{i,1}$. From Ref. [1], its time derivative is $\dot{z}_{i,1} = g_{i,1}x_{i,2} + \theta_{i,1}^{\top} f_{i,1} + d_{i,1} + h_{i,1} - \dot{y}_{i,r}$. Then, we consider a Lyapunov function candidate $V_{i,1} = (1/(2g_{i,1}))z_{i,1}^2$. The time