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Composite anti-disturbance control for a discrete-time time-varying delay system with actuator failures based on a switching method and a disturbance observer

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HIGHLIGHTS

- The system is transformed to a switched system based on the information of actuator failures.
- A disturbance observer is constructed to estimate the disturbances.
- Combining disturbance observer and exponential $l_2 - l_\infty$ performance index, a controller is given.

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ABSTRACT

The composite anti-disturbance control problem is developed for discrete-time systems with both time-varying delay and multiple disturbances under actuator failures in this paper. First, depending on the information of actuator failures, the system is transformed into a switched system. Then, considering the switched system, the composite controller is designed via a disturbance observer based control and an exponential $l_2 - l_\infty$ control method. A disturbance observer is constructed to estimate the disturbances generated by an exogenous system, and the estimated value is introduced into a memory exponential $l_2 - l_\infty$ state feedback control law, such that, the closed-loop system is asymptotically stable, and different types of disturbances are rejected and attenuated. Third, by resorting to the average dwell time approach and the free-weighting matrix technique, some sufficient criteria for the desired disturbance observer and the state feedback controller are established, and the corresponding solvability conditions using a cone complementarity linearization method are presented. A numerical example is provided to demonstrate the effectiveness of the proposed algorithms finally.

1. Introduction

With the scale aggrandizement and increasing complexity of control systems, the study of reliable control becomes very important. Actuator failures inevitably encounter in actual systems due to the aging of the actuator components and the changes in the external environment. Once some actuators fail to work, the reliability of the system will degrade, so how to design an appropriate controller such that the closed-loop system can tolerate some specific control component failures and preserve the stability of the overall system will be very meaningful. In recent years, considerable amount of attention has been paid to design the reliable controller with actuator failures [1–4].

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On the other hand, it is well known that time delay exists commonly in dynamic systems and is frequently a source of instability, oscillation, and poor performance. Many efforts have been devoted to studying the continuous/discrete-time system with time delay under actuator failures [5–7]. For example, the authors in [5] developed an adaptive state feedback coordinated decentralized control scheme for a class of dynamic systems with state delay and unknown actuator failures. By regarding the outputs of faulty actuators as disturbance inputs, the synthesis problem of delay-dependent robust and reliable H_∞ control was addressed in [6] for linear time-delay systems with actuator failures. In [7], the reliable H_∞ control problem was investigated for discrete-time piecewise linear systems with time delays and actuator failures. In addition, disturbances widely exist in most engineering systems and always bring adverse effects on control performance of the closed-loop systems. In order to obtain disturbance attenuate performance, some performance indexes, for example, $H_\infty, L_2 - L_\infty$ $(l_2 - l_\infty)$, and exponential $l_2 - l_\infty$, are introduced to deal with external disturbances in controller design. Numerous meaningful results have been presented with these performance indexes [8–16]. However, the disturbances considered therein are needed to satisfy an H_2 norm bounded. To further enhance disturbance attenuation and rejection performance of the closed-loop system, disturbance observer based control (DOBC) method has been researched from 1980s and used in many control fields [17–29]. The basic idea of this method is that a disturbance observer is constructed and the output of the disturbance observer is employed to feedforward compensation.

During the past decades, switched systems have received more and more attention due to the widespread existence of switching characteristic in practical systems. Lyapunov function has been widely used to deal with the stability problem of switched systems [8,30–34]. The average dwell time approach has been shown to be an effective tool for choosing certain switching laws, under which the exponential stability can be obtained [35–40]. Recently, a switching control approach has been proposed to deal with the problem of reliable control with actuator failures [41–43]. The key idea is to view a non-switched system with actuator failures as a switched system with switching signal depending on the information of actuator failures. The problem of exponential stability was studied for a class of uncertain time-varying delay systems with actuator failures in [41], and a hybrid dynamical output feedback controller was designed. In addition, the output feedback stabilization problem for a class of uncertain linear systems with faulty actuators was studied via the synergy with a switching strategy in [42]. Note that among the above mentioned literature of actuator failures problem, the system has been supposed to be subject to any disturbances or just one kind of disturbances. However, it does not conform with the practice. The system is always affected by many kinds of disturbances, for example, norm-bounded disturbances, disturbances with some known information, and so on. To the best of the authors' knowledge, the controller design for the discrete-time systems with actuator failures and multiple disturbances has not been fully investigated.

In this paper, a composite anti-disturbance controller is developed for discrete-time systems with both time-varying delay and multiple disturbances under actuator failures. First, the system is transformed into a switched system based on the information of actuator failures. Then, the composite controller is designed via DOBC and an exponential $l_2 - l_\infty$ control method for an obtained switched system, where different types of disturbances are rejected and attenuated by different methods, i.e., a disturbance observer is constructed to estimate the disturbances generated by an exogenous system, and an exponential $l_2 - l_\infty$ performance index is introduced to attenuate the norm bounded disturbances. Third, some sufficient criteria for the desired disturbance observer and state feedback controller are presented via the average dwell time approach and the free-weighting matrix technique, and the corresponding solvability conditions using a cone complementarity linearization method are given. Finally, the effectiveness of the proposed composite control scheme is demonstrated by a numerical example.

2. Problem formulation and preliminaries

Consider the following discrete-time systems with time-varying delay (Σ_0)

$$x(k+1) = Ax(k) + A_d x(k-\tau(k)) + B_2(u(k) + d_2(k)) + B_1 d_1(k), \tag{1}$$

$$z(k) = Cx(k) + C_d x(k-\tau(k)), \tag{2}$$

$$x(s) = \phi(s), \quad s = -\overline{\tau}, -\overline{\tau}+1, \ldots, 0,$$

where $x(k) \in \mathbb{R}^n$, $u(k) \in \mathbb{R}^p$ and $z(k) \in \mathbb{R}^q$ are the state, control input and controlled output, respectively, A, A_d, B_1, B_2, C, C_d are constant matrices of appropriate dimensions, $\tau(k)$ denotes the time-varying state delay satisfying

$$0 < \underline{\tau} \le \tau(k) \le \overline{\tau}, \quad \forall k \in \mathbb{Z}^+, \tag{3}$$

where $\underline{\tau}$ and $\overline{\tau}$ are positive integer numbers, $\phi(s)$ represents the initial condition. $d_1(k) \in \mathbb{R}^m$ is the disturbance input, which is assumed to belong to $l_2[0, \infty)$, $d_2(k) \in \mathbb{R}^p$ is the external disturbances, which is generated by the exogenous system [29]

$$\omega(k+1) = W\omega(k) + H\delta(k), \qquad d_2(k) = V\omega(k), \tag{4}$$

where W, V, H are known matrices, and $\delta(k) \in l_2[0, \infty)$ is the additional disturbances.

In practical situations, actuator failures may encounter sometimes. Since actuators are very important in transforming the controller output to the plant, how to preserve the closed-loop system performance in the case of actuator failures becomes very meaningful. In what follows, we will transform the given system to a switched system depending on the information of actuator failures. When an actuator fails, the value of the corresponding column of B_2 will become zero, and a new model that