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Error-constrained reliable tracking control for discrete time-varying systems subject to quantization effects ☆

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ABSTRACT

In this paper, the reliable tracking control problem based on set-membership idea is investigated for the discrete time-varying systems subject to time-delays, quantization effects and parameter uncertainties. The failures of actuators are quantified by a variable varying in a given interval. The norm-bounded uncertainty enters into the system matrices, and the quantizer is assumed to be of the logarithmic type, as well as the measurement noises and process noises are formulated as unknown but bounded and confined in ellipsoidal sets. The aim of the addressed reliable tracking control problem is to design an observer-based controller, such that, for the admissible time-delays, uncertainties, unknown but bounded noises, quantization effects and actuator failures, both the tracking error and the estimation error are not more than certain upper bounds that can be minimized at each time instant. Several sufficient conditions for the existence of observers and reliable controllers are derived in terms of the solutions to certain matrix inequalities that can be solved effectively by using available software. Finally, a simulation practical example is employed to show the effectiveness of the proposed design scheme.

1. Introduction

The past few decades have witnessed a surge of research interest on the tracking control due to clear engineering insights in many practical applications involving spacecraft attitude tracking control, robotic trajectory tracking control and missile control and so on. Up to now, considerable efforts have been made on the tracking control issues and a rich body of literature has been available [1–7], besides, among them, there are many approaches to designing tracking controller. For instance, a linear matrix inequality (LMI)-based procedure has been proposed in [2] to guarantee that the output of the closed-loop networked control systems tracks the output of a given reference model well in the H_∞ sense. In [4], the direct adaptive-state feedback laws have been developed for linear time-invariant plants with actuator failures, and the closed-loop stability and asymptotic-state tracking have been ensured. In [8], the H_∞ decentralized fuzzy control method has been proposed, furthermore, the stability of the nonlinear interconnected systems has been guaranteed. It should be pointed out that the literature mentioned above is related to the time-invariant cases, however, almost all real-time systems are time-varying and therefore the finite-horizon tracking control problem is of practical significance. What is more, in many cases, the states may be unavailable, which should design a state observer to estimate the system state. Yet, so far, there have been very few results in the literature [9] regarding observer-based reliable control problems over the finite horizon, which arouses one of the motivations of this paper.

Conventional feedback control design for a multi-input–multi-output plant may result in unsatisfactory control system performance, or even instability, in the event of actuator or sensor outages, even though it may be possible to control the plant using only the surviving inputs and outputs. It is therefore of interest to develop feedback control designs, which may guarantee satisfactory closed-loop behavior in despite of actuator or sensor outages. This motivates the development of the so-called reliable control theory.

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In the past few decades, as an effective method, reliable control has attracted considerable amount of attention [10–14]. Several approaches have been proposed to deal with the reliable control problem, such as algebraic Riccati equation (ARE) approach and linear matrix inequality (LMI) approach. In detail, in [12], the problem of robust reliable control design has been concerned for a class of nonlinear uncertain state-delay systems, and the algebraic Riccati equation approach has been developed to solve the problem addressed. Ref. [13] has studied the design problem of reliable H_∞ controller with adaptive mechanism for linear systems, which the design conditions have been given in terms of solutions of a set of linear matrix inequalities (LMIs). The resultant designs can guarantee the asymptotic stability and adaptive H_∞ performance of the closed-loop systems in the cases of actuator failures. It is worth pointing out that, in most of the literature mentioned above, the reliable control problem has been considered for time-invariant systems. With respect to time-varying systems, finite-horizon reliable problems have not been thoroughly investigated yet. Very recently, in [15], the recursive matrix inequality approach has been employed to design the reliable H_∞ observer-based controller over the finite-horizon with randomly occurring uncertainties and nonlinearities, as well as quantization effects. However, to the best of the authors' knowledge, such a system for tracking control problem has not been adequately investigated. It is, therefore, the other purpose of this paper to deal with this problem.

Set-membership or set-valued state estimation which provides a set of state estimates containing the system's true state under the assumptions of bounded noises was proposed first at the end of 1960s and early 1970s, see [16–18]. These results aimed to compute the state estimate ellipsoid given the perturbations and noises. In the past few decades, the idea of ellipsoid estimation has been extensively investigated and many approaches have been adopted, especially, a very popular method also employed in this paper has attracted a growing research interest proposed by [19], and along this method, many achievements have been obtained, see [20–22]. To our best knowledge, using set-membership idea to minimize estimation error and tracking error has not been adequately addressed for reliable tracking control problem, which stirs our research interest.

As is well known, it is ubiquitous and unavoidable existence of the inherent time delays and parameter uncertainties contained in the dynamical behavior of many physical processes. In the past few years, we have witnessed significant advances in the study of the robust problem for time-delay systems. On the one hand, owing to the finite switching speed of the amplifiers, time-delays are frequently encountered in dynamical systems, which may deteriorate the system performance and even result in the instability of the systems. Much effort has been devoted to various types of delays, such as constant time-delay [23,24], time-varying delay [25], distributed delay [26–28], randomly occurring delay [29] as well as their combinations [30,31]. On another hand, because of the inevitable external disturbances, the parameter uncertainty widely exists in the system matrices, including polytopic uncertainty, stochastic parameter uncertainty and norm-bounded uncertainty, see [12,30–33]. Besides, based on the standard assumption that data transmission required by the system can be performed with infinite precision, it is not valid in the presence of signal quantization or capacity-limited case, and therefore there is necessary to consider the quantization effects during the network transmission. The study on the quantization has obtained many achievements [34–38]. However, when it comes to the reliable tracking control problem involving time-delay and parameter uncertainty for time-varying systems, the related results are very few, not to mention the case when measurement quantization is also taken into account. Therefore, another purpose of this paper is to shorten such a gap.

Summarizing the above discussions, to handle the four identified challenges, the focus of this paper is to deal with reliable tracking control problem based on the error constraints for a class of discrete time-varying systems subject to quantization effects, parameter uncertainties as well as actuator failures. The main contributions of this paper can be highlighted as follows: (1) *The set-membership idea is, for the first time, considered in the event of the actuator failures for the reliable tracking control problem.* (2) *The system under consideration is comprehensive to cover uncertainty parameters, actuator failures, time-delays, and measurement quantization, hence reflecting the reality more closely.* (3) *For the reliable tracking control problem in the presence of actuator failures, two kinds of optimized error upper bounds are obtained by solving a set of recursive linear matrix inequalities at each time instant.*

The rest of this paper is outlined as follows. In Section 2, the reliable tracking control problem is introduced for a class of discrete time-varying systems with time-delays, parameter uncertainties, actuator failures, bounded noises as well as quantization effects, and some lemmas are prepared. In Section 3, sufficient conditions are derived to guarantee the existence of the desired observers and controllers by solving minimization problems subject to some inequality constraints. A simulation example is given in Section 4 to demonstrate the main results obtained. Finally, we conclude the paper in Section 5.

Notation: The notation used here is standard except where otherwise stated. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space. $\mathbb{Z}^+$ denotes the set of nonnegative integers. The notation $X \geq Y (X > Y)$, where X and Y are real symmetric matrices, means that $X - Y$ is positive semi-definite (positive definite). $\mathrm{tr}\{A\}$ stands for the trace of A. The shorthand $\mathrm{diag}\{\cdots\}$ represents a block-diagonal matrix. A^T stands for the transpose of A. Matrices, if they are not explicitly specified, are assumed to have compatible dimensions.

2. Problem formulation and preliminaries

Consider the following discrete time-varying uncertain systems subject to time-delay:

$$\begin{cases} x(k+1) = A(k)x(k) + A_d(k)x(k-d) + B(k)u(k) + E(k)w(k), \\ y(k) = C(k)x(k) + D(k)v(k), \\ x(k) = \psi(k), \quad k \in [-d, 0] \end{cases} \tag{1}$$

where $x(k) \in \mathbb{R}^n$ is the state; $y(k) \in \mathbb{R}^m$ is the measurement output; $u(k) \in \mathbb{R}^q$ is the control input; $d \in \mathbb{Z}^+$ is a constant delay; $\psi(k)$ is the initial state of the system. For a given time instant k, $B(k)$, $E(k)$, $C(k)$ and $D(k)$ are known matrices with appropriate dimensions; $A(k) = \overline{A}(k) + \Delta A(k)$, $A_d(k) = \overline{A}_d(k) + \Delta A_d(k)$ with $\Delta A(k)$ and $\Delta A_d(k)$ being unknown matrices representing parameter uncertainties in the following form:

$$[\Delta A(k)\ \Delta A_d(k)] = M(k)F(k)[N(k)\ N_d(k)]$$

where $M(k)$, $N(k)$ and $N_d(k)$ are known time-varying matrices with appropriate dimensions. $F(k)$ is an unknown time-varying matrix satisfying $F^T(k)F(k) \leq I$.

$w(k)$ and $v(k)$ are the process noises and measurement noises, respectively which are unknown, bounded and confined to the following specified ellipsoidal sets:

$$\mathcal{W} = \{w(k) : w^T(k)Q^{-1}(k)w(k) \leq 1\}, \tag{2}$$

$$\mathcal{V} = \{v(k) : v^T(k)R^{-1}(k)v(k) \leq 1\} \tag{3}$$

where $Q(k)$ and $R(k)$ are known positive-definite matrices with compatible dimensions, which denote the “shape” of the ellipsoids with 0 being the center.