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Short communication

Combined feedback–feedforward tracking control for networked control systems with probabilistic delays

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Abstract

In this paper, we investigate the combined feedback–feedforward tracking control problem for networked control systems (NCSs) under the discrete-time framework. Network-induced delays, both on the network links from the sensor to the controller (S–C) and from the controller to the actuator (C–A), are considered. It is assumed that the probability for the occurrence of each delay is known within a set. We apply a predictive scheme to compensate for the C–A delay, and propose to design a controller for each network-induced delay. Using the augmentation technique twice, the tracking problem of the NCS is converted to a feedback control problem for delay-free stochastic systems. The stochastic stability and the $\mathcal{H}_\infty$ performance of the obtained closed-loop stochastic system are analyzed in terms of a linear matrix inequality and a linear matrix equality. Then, we propose the controller design method by solving a nonlinear trace minimization problem. Finally, an example on the control of a helicopter is given to illustrate the proposed design approach.

1. Introduction

Networked control systems (NCSs) have attracted considerable attention in the past few years, and have found applications in a broad range of areas; see a recent survey [1] and the references therein. Though a shared network has many advantages over the conventional point-to-point connection [2], the insertion of the network medium leads to problems such as quantization,

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sampling and network-induced delays and packet dropouts [3]. Recently, some progress has been made to deal with the network-induced issues for NCSs. The authors in [4] studied random network-induced delays modeled by Markovian chains. Both network-induced delays and packet dropouts were considered in sample-data NCSs for the controller design problem in [5,6]. The controller design problem for NCSs with multiple-packet transmission was investigated in [7]. The results of networked predictive control for systems with random network delays in both forward and feedback channels were exploited in [8]. In [9], the controller synthesis problem for NCSs was investigated by incorporating time-varying intervals, delays, and packet dropouts.

Although there has been considerable work on NCSs, most of the effort has been devoted to determining stability conditions, stabilization and filter design. In contrast, the tracking problem has gained relatively less attention. The authors in [10] proposed a controller design method to track the output of a reference model in a networked environment. However, in practice, it is always required that the output of the plant tracks the reference itself well. The reference tracking problem for sampled-data systems with feedforward and feedback (Proportional) control was dealt with in [11]. As the proportional-integral-derivative control is dominant in industrial feedback control loops and only a proportional control cannot always achieve a good tracking performance, it is natural to attempt to combine the feedforward and feedback (Proportional-Integral-Derivative) control for the reference tracking problem of NCSs, which is the motivation of this paper.

In this paper, we study the tracking problem for NCSs. A combined feedforward–feedback control configuration is employed. We utilize a modified proportional-integral-derivative control scheme in the feedback control loop. Note that the controller does not know the time delay for the control signal transmitted from the controller node to the actuator node. In order to compensate for the time delay on the link from the controller to the actuator, we employ a predictive control scheme [8], that is, we generalize a series of control signals which are dependent on each of the possible delay on the link from the controller to the actuator. The generated control signals are packed together and sent to the actuator node. At the actuator node, it is easy to obtain the accumulated delays induced by the network links. We assume that each delay has an occurrence probability which is known *a priori*. The generated control signals are dependent on the delays and the occurrence probabilities. When the packed control signals arrive at the actuator node, the control signal is chosen according to the accumulated delay. Using the augmentation technique, we obtain a delay-free closed-loop system with stochastic parameters. The stochastic stability and $\mathcal{H}_\infty$ performance [12,13] are studied for the closed-loop system. Control gains can be derived by solving a nonlinear optimization problem.

Notation: The notations used in this paper are fairly standard. Superscript “T” indicates the matrix transposition; $\mathbb{R}^n$ denotes the n-dimensional Euclidean space; $\mathbb{E}\{z\}$ stands for the expectation of the stochastic variable z; and Prob{“ · ”} means the occurrence probability of an event “·”. In addition, in symmetric block matrices or long matrix expressions, we use $*$ as an ellipsis for the terms that are introduced by symmetry and diag $\{\cdots\}$ as a block-diagonal matrix. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations. For a matrix P, the notations $P=P^{\mathrm{T}}>0$, $P=P^{\mathrm{T}}<0$, and $P=P^{\mathrm{T}}\geq 0$ mean that P is positive definite, negative definite, and semi-positive definite, respectively.

2. Problem formulation

Consider a typical tracking control problem for NCSs, as shown in Fig. 1. The output of the plant is transmitted to the tracking controller via a communication link. The tracking controller