Set-Based Detection and Isolation of Intersampled Delays and Pocket Dropouts in Networked Control

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Abstract. This paper focuses on the set-based method for detection and isolation of the network-induced time-delays and packet dropouts. We particularly pay attention to the systems described by a linear discrete-time equation affected by additive disturbances, controlled via redundant communication channels prone to intersampled time-delays and packet dropouts. Time-delays and packet dropouts are considered as faults from a classical control theory perspective. We will show that fault detection and isolation can be achieved indirectly through the separation of positively invariant sets that correspond to the closed-loop dynamics with healthy and faulty communication channels. For this purpose, in order to provide a reference signal that uniquely guarantees the fault detection and isolation in real time, we design a reference governor using receding horizon technique.

Keywords: Fault detection and isolation, time-delay systems, positively invariant sets.

1 Introduction

High technical demands on safety and performance, for instance in modern aeronautics, require application of redundant sensors and actuators. Unfortunately, numerous examples in practice testify that malfunction in actuation (see Maciejowski and Jones [2003]) and sensing systems (see BEA [2012]) sometimes could end with fatal consequences. Therefore, a great effort has been put in development of control systems which, based on the built-in redundancy, can tolerate malfunctions while maintaining desirable performance (see e.g. Blanke [2003], Seron et al. [2008], Olaru et al. [2010]).

In practical applications, communication between various components in the loop is attained via imperfect channels. Despite the advantages that they brought in control, real networks are prone to undesirable effects such as time-delays (e.g. network access and transmission delays) and packet dropouts due to network
congestion or transmission errors in physical links (see Hespanha et al. [2007]). Since the presence of time-delays has mostly destabilizing effect, their consideration may be crucial for the overall system behavior (see e.g. Niculescu [2001], Sipahi et al. [2011]). Time-delays and packet dropouts in control over real networks have been exhaustively treated in the literature (see for instance Zhang et al. [2001] and Hespanha et al. [2007]). In most of these works, analysis has been carried out from the robustness point of view i.e. to detect the maximal time-delay in a communication channel (sensor-to-controller and/or controller-to-actuator) which preserves desirable closed-loop behavior. On the other side, an active strategy for constant delay detection and isolation has been recently proposed in Stanković et al. [2012].

A set theoretic approach, based on switching multi-sensor network, with fault detection and isolation (FDI) capabilities in the feedback loop, was proposed by Seron et al. [2008]. It was assumed that sensors were deterministic with additive disturbance while the FDI was achieved through invariant sets separation. The main advantage of such approach was the efficient implementation that required only set membership testing, while all invariant sets were computed offline. The drawback of the method, however, was a priori fixed range of the reference signal. Consequently, an unfortunate choice of the reference may render the detection infeasible. Guided by the generic idea that systems can often manage some modest deviations in the reference signal, Stoican et al. [2012] proposed a solution for this limitation introducing a reference governor in the loop, thus considerably increasing operational range of the method.

Building upon the results of Stoican et al. [2012], Seron et al. [2008], Olaru et al. [2010], and Stanković et al. [2012] in the present note we develop a FDI switching scheme for intersampled time-delays (less than a sampling period) and/or packet dropouts. The usefulness of the proposed method is outlined by an example where even such small time-delays are destructive for the overall performance of the closed-loop dynamics.

The present article is organized as follows. The following section discuss the propose FDI scheme and the problem formulation. The Section 3 outlines results on the construction of the positively invariant sets. Section 4 addresses the fault detection and isolation scenario while Section 5 deals with the reference governor design. Numerical example is provided in the Section 6 and Section 7 presents our conclusions.

Notations

Denote with $\mathbb{R}$, and $\mathbb{Z}$ sets of real and integer numbers, respectively. The closed interval of integers is defined as $\mathbb{Z}_{[a,b]} = \{i : a \leq i \leq b, a, b \in \mathbb{Z}\}$.

Notations $x[k+1]$, $x[k]$ and $x[k-1]$ denote the successor, current and predecessor states, respectively. The Minkowski sum of two sets, $\mathcal{P}$ and $\mathcal{Q}$, is denoted by

$$\mathcal{P} \oplus \mathcal{Q} = \{x : x = p + q, p \in \mathcal{P}, q \in \mathcal{Q}\}.$$ 

Interior of a set $\mathcal{S}$ is denoted by $\text{int}(\mathcal{S})$ while the convex hull by $\text{conv}(\mathcal{S})$. For the $p$-norm of a vector we use the standard definition, $\|x\|_p = (\sum_{i=1}^{n} |x_i|^p)^{1/p}$.