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Brief paper

Decentralized networked control of systems with local networks: A time-delay approach ☆

Dror Freirich, Emilia Fridman

School of Electrical Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel

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ABSTRACT

This paper develops the time-delay approach to large-scale networked control systems (NCSs) with multiple local communication networks connecting sensors, controllers and actuators. The local networks operate asynchronously and independently of each other in the presence of variable sampling intervals, transmission delays and scheduling protocols (from sensors to controllers). The communication delays are allowed to be greater than the sampling intervals. A novel Lyapunov–Krasovskii method is presented for the exponential stability analysis of the closed-loop large-scale system. In the case of networked control of a single plant our results lead to simplified conditions in terms of reduced-order linear matrix inequalities (LMIs) comparatively to the recent results in the framework of time-delay systems. Polytopic type uncertainties in the system model can be easily included in the analysis. Numerical examples from the literature illustrate the efficiency of the results.

1. Introduction

Networked Control Systems are systems with spatially distributed sensors, actuators and controller nodes which exchange data over a communication data channel (Antsaklis & Baillieul, 2007). It is important to provide a stability and performance certificate that takes into account the network imperfections (such as variable sampling intervals, variable communication delays, scheduling protocols, etc.). The hybrid system approach has been applied to nonlinear NCSs under Try-Once-Discard (TOD) and Round-Robin (RR) scheduling protocols in Heemels, Teel, van de Wouw, and Nesic (2010), Nesic and Teel (2004), Walsh, Ye, and Bushnell (2002), where variable sampling intervals and *small communication delays* (that are smaller than the sampling intervals) have been considered. Recently the time-delay approach to NCSs (see e.g. Fridman, 2014; Fridman, Seuret, & Richard, 2004; Gao, Chen, & Lam, 2008) was extended to networked systems under TOD and RR protocols that allowed to treat *large communication delays* (Liu, Fridman, & Hetel, 2012, 2015).

It is common place in industry that the total plant to be controlled consists of a large number of interacting subsystems (Lunze, 1992). Usually the control of the plant is designed in a decentralized manner with local control stations allocated to individual subsystems. Most papers on NCSs assume that there is one controller and one global communication network. However, in the control of large-scale systems it is more efficient to use local controllers and local networks instead of the global ones. This leads to large-scale NCSs with independent and asynchronous local networks. Another application of NCSs with asynchronous local networks is platoons of vehicles that communicate wirelessly without timing coordination between members of the whole string (Heemels, Borgers, van de Wouw, Nesic, & Teel, 2013).

Decentralized networked control of large-scale interconnected systems with local independent networks was studied in the framework of hybrid systems (Borgers & Heemels, 2014; Heemels et al., 2013), where variable sampling or/and small communication delays were taken into account. Distributed estimation in the presence of *synchronous* sampling of local networks and RR protocol was recently analyzed in Ugrinovskii and Fridman (2014) in the framework of time-delay approach.

The goal of this paper is to extend the time-delay approach to decentralized NCS with multiple local communication networks connecting sensors, controllers and actuators. The local networks operate asynchronously and independently of each other in the presence of variable sampling intervals, transmission delays and scheduling protocols (from sensors to controllers). The

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E-mail addresses: drorfrc@gmail.com (D. Freirich), emilia@eng.tau.ac.il (E. Fridman).

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communication delays are allowed to be greater than the sampling intervals. Note that direct extension of the switched system modeling under RR protocol of Liu et al. (2012) to large-scale system would lead to numerous LMIs. The Lyapunov–Krasovskii method of Liu et al. (2015) developed for hybrid time-delay models of the closed-loop systems under TOD and RR protocols involves complicated conditions on the derivative and on the jumps of Lyapunov functionals that cannot be directly extended to large-scale systems.

In the present paper a novel Lyapunov–Krasovskii method is suggested for the exponential stability analysis of the closed-loop large-scale system. In the case of networked control of a single plant our results lead to simplified conditions in terms of reduced-order LMIs comparatively to the recent results (Liu et al., 2012, 2015). Numerical examples from the literature illustrate the efficiency of the results.

Notation: Throughout the paper the superscript 'T' stands for matrix transposition, $\mathbb{R}^n$ denotes the n dimensional Euclidean space with vector norm $|\cdot|$, $\mathbb{R}^{n\times m}$ is the set of all $n\times m$ real matrices, and the notation $P > 0$, for $P \in \mathbb{R}^{n\times n}$ means that P is symmetric and positive definite. The symmetric elements of the symmetric matrix will be denoted by $*$. The space of functions $\phi : [a, b] \to \mathbb{R}^n$, which are absolutely continuous on $[a, b]$ and have square integrable first-order derivatives, is denoted by $W[a, b]$ with the norm $\|\phi\|_W = \|\phi\|_{W[a,b]} = \max_{\theta\in[a,b]} |\phi(\theta)| + \left[\int_a^b |\dot{\phi}(s)|^2 ds\right]^{\frac{1}{2}}$. $\mathbb{Z}_+$ and $\mathbb{N}$ denote the set of non-negative integers and positive integers, respectively. *MATI* and *MAD* denote maximum allowable transmission interval and maximum allowable delay, respectively. Denote by δ_{nm} the Kronecker delta meaning $\delta_{nm} = 0$, $n \neq m$ and $\delta_{nn} = 1$ $(n, m \in \mathbb{N})$. Throughout the paper the subscript or superscript j stands for a subsystem index, while subscript i denotes the sensor index.

2. Problem formulation

Consider the system in Fig. 1, consisting of M physically coupled linear continuous-time plants Pj, controlled by M local controllers Cj $(j = 1, \ldots, M)$. The dynamics of the plants Pj are given by subsystems:

$$\dot{x}_j(t) = A_j x_j(t) + \sum_{l\neq j} F_{lj} x_l(t) + B_j u_j(t), \quad t \geq 0, \qquad (1)$$
$$x_j(0) = x_{0j},$$

where $j = 1 \ldots M$ is the subsystem index, $x_j(t) \in \mathcal{R}^{n^j}$ is the state, $u_j(t) \in \mathcal{R}^{m^j}$ is the control input, A_j, B_j and F_{lj} are matrices of appropriate dimensions. Subsystem j has several nodes (N_j distributed sensors, a controller node and an actuator node) connected via a local communication network. The measurements are given by

$$y_{ij}(t) = C_{ij} x_j(t) \in \mathbb{R}^{n_i^j}, \quad i = 1, \ldots, N_j, \qquad \sum_{i=1}^{N_j} n_i^j = n_y^j.$$

The jth subsystem is assumed to have an independent sequence of sampling instants

$$0 = s_0^j < s_1^j < \cdots < s_k^j < \cdots, \qquad \lim_{k\to\infty} s_k^j = \infty$$

with bounded sampling intervals $s_{k+1}^j - s_k^j \leq MATI_j$. At each s_k^j, one of the outputs $y_{ij}(s_k^j) \in \mathbb{R}^{n_i^j}$ is transmitted via the sensor network to controller Cj.

Suppose that data loss is not possible and that the transmission of the information over the networks from sensors to actuators is subject to a variable roundtrip delay η_k^j. Then $t_k^j = s_k^j + \eta_k^j$ is the updating time instant of the Zero-Order Hold (ZOH). Communication delay is assumed to be bounded $\eta_k^j \in \left[\eta_m^j, \eta_M^j\right]$, where $\eta_M^j \triangleq MAD_j$. Differently from Borgers and Heemels (2014), we do not restrict the network delays to be small with $t_k^j = s_k^j + \eta_k^j < s_{k+1}^j$, i.e. $\eta_k^j < s_{k+1}^j - s_k^j$. As in Naghshtabrizi, Hespanha, and Teel (2010) we allow the delay to be non-small provided that the old sample cannot get to the same destination (same controller or same actuator) after the most recent one. We suppose that the controllers and the actuators are event-driven (in the sense that they update their outputs as soon as they receive a new sample).

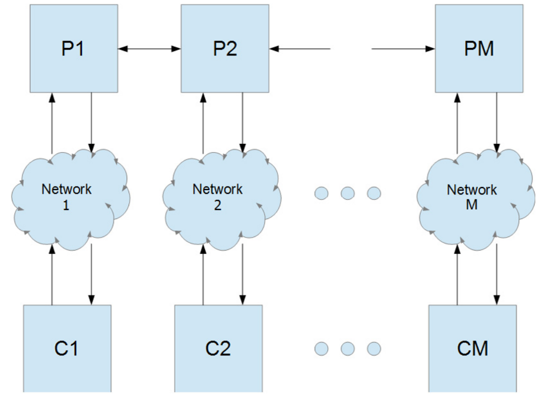

Fig. 1. Decentralized control of systems with local networks.

Assume the following assumption:

A1 There exist M gain matrices $K_j = \begin{bmatrix} K_{1j} & \cdots & K_{N_j j}\end{bmatrix}$, $K_{ij} \in \mathbb{R}^{m^j\times n_i^j}$ such that the matrices $A_j + B_j K_j C_j$ are Hurwitz, where $C_j = \begin{bmatrix} C_{1j}^T & \cdots & C_{N_j j}^T\end{bmatrix}^T$.

Remark 1. The assumption **A1** means that the "nominal system" $\dot{x}_j = A_j + B_j u_j$ is stabilizable by a static output-feedback $u_j = K_j C_j x_j$. Note that in the case of only one network (from sensors to controller) in each subsystem, the presented results can be easily adapted to decentralized observer-based control of large-scale systems as shown for the case of one plant in Liu et al. (2012, 2015).

We will consider TOD and RR protocols that orchestrate the sensor data transmission to the controller. Denote $J = \{1, \ldots, M\}$, $J_{RR} = \{j \in J |\ j\text{th subsystem is under RR}\}$ and $J_{TOD} = \{j \in J |\ j\text{th subsystem is under TOD}\}$. Note that if for some j there is no scheduling from the sensors ($N_j = 1$) to the controller we will refer to it as $j \in J_{RR}$, where $N_j = 1$. Thus, $J = J_{RR} \bigcup J_{TOD}$. Denote by

$$\hat{y}_j(s_k^j) = \begin{bmatrix} \hat{y}_{1j}^T(s_k^j) & \cdots & \hat{y}_{N_j j}^T(s_k^j)\end{bmatrix}^T \in \mathbb{R}^{n_y^j} \qquad (2)$$

the most recent output information submitted to the scheduling protocol of the jth subsystem (i.e. the most recent information at the jth controller side) at the sampling instant s_k^j. Then under **A1** the resulting static output-feedbacks are given by

$$u_j(t) = \sum_{i=1}^{N_j} K_{ij} \hat{y}_{ij}(s_k^j), \quad t \in [t_k^j, t_{k+1}^j),$$
$$k \in \mathbb{Z}_+,\ j = 1 \ldots M. \qquad (3)$$

Denote

$$T \triangleq \max\{\{t_{N_j-1}^j\}_{|j\in J_{RR}}, \{t_0^j\}_{|j\in J_{TOD}}\},$$
$$x(t) = col\{x_1(t), \ldots, x_M(t)\}. \qquad (4)$$