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Decentralized observer-based control via networked communication ☆

N.W. Bauer [1], M.C.F. Donkers, N. van de Wouw, W.P.M.H. Heemels

Department of Mechanical Engineering, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

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ABSTRACT

This paper provides one of the first approaches to the design of decentralized observer-based output-feedback controllers for linear plants where the controllers, sensors and actuators are connected via a shared communication network subject to time-varying transmission intervals and delays. Due to the communication medium being shared, it is impossible to transmit all control commands and measurement data simultaneously. As a consequence, a protocol is needed to orchestrate what data is sent over the network at each transmission instant. To effectively deal with the shared communication medium using observer-based controllers, we adopt a switched observer structure that switches based on the available measured outputs and a switched controller structure that switches based on available control inputs at each transmission time. By taking a discrete-time switched linear system perspective, we are able to derive a general model that captures all these networked and decentralized control aspects. The proposed synthesis method is based on decomposing the closed-loop model into a multi-gain switched static output-feedback form. This decomposition allows for the formulation of linear matrix inequality based synthesis conditions which, if satisfied, provide stabilizing observer-based controllers, which are both decentralized and robust to network effects. A numerical example illustrates the strengths as well as the limitations of the developed theory.

1. Introduction

Recently, there has been an enormous interest in the control of large-scale networked systems that are physically distributed over a wide area (Murray, Åström, Boyd, Brockett, & Stein, 2003). Examples of such distributed systems are electrical power distribution networks (Blaabjerg, Teodorescu, Liserre, & Timbus, 2006), water transportation networks (Cembrano, Wells, Quevedo, Pérez, & Argelaguet, 2000), industrial factories (Moyne & Tilbury, 2007) and energy collection networks (such as wind farms Johnson & Thomas, 2009). The purpose of developing control theory in this large-scale setting is to work towards the goal of a streamlined design process which consistently results in efficient operation of these vital systems. Our contribution towards this goal is in the area of stabilizing controller design. This problem setting has many features that seriously challenge controller design.

The first feature which challenges controller design is that the controller is decentralized, in the sense that it consists of a number of local controllers that do not share information. Although a centralized controller could alternatively be considered, the achievable bandwidth associated with using a centralized control structure would be limited by long delays induced by the communication between the centralized controller and distant sensors and actuators over a (wireless) communication network (Al-Hammouri, Branicky, Liberatore, & Phillips, 2006). The difficulty of decentralized control synthesis lies in the fact that each local controller has only local information to utilize for control, which implies that the other local control actions are unknown and can be perceived as disturbances. This fundamental problem has received ample attention (Anderson & Moore, 1981; Sandell, Varaiya, Athans, & Safonov, 1978; Šiljak, 1991), but still many issues are actively researched today. A recent survey (Bakule, 2008) highlights newly developed techniques to solve this problem in different settings and recommends that research should consider interconnected systems which are controlled over realistic communication channels. This forms the exact topic of the presented paper.

The problem of synthesizing decentralized linear controllers is often referred to as the 'information-constrained' synthesis problem or the 'structured' synthesis problem due to the presence of zeros in the controller matrices corresponding to the decentralized structure. This synthesis problem is, in general, non-convex. It was shown in Rotkowitz and Lall (2005) that linear time-invariant systems which satisfy a property called 'quadratic invariance', with respect to the controller information structure, allow for convex synthesis of optimal static feedback controllers. For the specific case of block diagonal *static state* feedback

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E-mail addresses: n.w.bauer@tue.nl (N.W. Bauer), m.c.f.donkers@tue.nl (M.C.F. Donkers), n.v.d.wouw@tue.nl (N. van de Wouw), m.heemels@tue.nl (W.P.M.H. Heemels).

[1] Tel.: +31 40 247 2072; fax: +31 40 246 1418.

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control design, (Geromel, Bernussou, & Peres, 1994) discovered that through a change of variable, linear matrix inequality (LMI) synthesis conditions could be formulated which guarantee robust stability. However, in the decentralized (block diagonal) dynamic output-feedback setting, the (robust) controller synthesis problem is far more complex (Stanković, Stipanović, & Šiljak, 2007).

The second feature which challenges controller design comes from the fact that when considering control of a large-scale system, it would be unreasonable to assume that all states are measured. Therefore an output-based controller is needed. This paper will, in fact, consider an observer-based control setup, which offers the additional advantage of reducing the number of sensors needed. The latter aspect alleviates the demands on the communication network design. However, it has been shown that, in general, it is hard to obtain decentralized observers providing state estimates converging to the 'true' states (Šiljak, 1991). In Stanković et al. (2007) and Zhu and Pagilla (2007), synthesis conditions for robust decentralized observer-based control with respect to unknown nonlinear subsystem coupling, which is sector bounded and state-dependent, were presented. In both papers, a decoupled quadratic Lyapunov function candidate was used to derive stabilizing gains that could be synthesized by transforming a linear minimization problem subject to a bilinear matrix inequality (BMI) into a two-step linear minimization problem subject to LMIs. It was also mentioned in Stanković et al. (2007) that in the simpler setting of the subsystem coupling matrices being linear and known, as is the setting in the current paper, the robust synthesis conditions are still obtained by convexifying the overlying problem of linear minimization subject to a BMI. Finally, we point out that all the aforementioned decentralized results, excluding the notable exception of Rotkowitz and Lall (2005) which includes communication delays, consider the communication channels between sensors, actuators and controllers to be *ideal*.

The third feature which challenges controller design arises from the fact that the implementation of a decentralized control strategy may not be economically feasible without a way to inexpensively connect the sensors, actuators and controllers. Indeed, the advantages of using a wired/wireless network compared to dedicated point-to-point (wired) connections between all sensors, controllers and actuators are inexpensive and easily modifiable communication links. However, the drawback is that the control system is susceptible to undesirable (possibly destabilizing) side-effects such as time-varying transmission intervals, time-varying delays, packet dropouts, quantization and a shared communication medium (the latter implying that not all information can be sent over the network at once). Clearly, the decentralized observer-based controller needs to have certain robustness properties with respect to these effects. For modeling simplicity, we only consider time-varying transmission intervals and the communication medium to be shared in this work, although extensions including the other side effects can be envisioned within the presented framework. In fact, the extension to including time-varying delays will be discussed explicitly in Remark 3.7.

In the Networked Control System (NCS) literature, there are many existing results on stability analysis which consider linear static controllers (Cloosterman, van de Wouw, Heemels, & Nijmeijer, 2009; Fujioka, 2008; Garcia-Rivera & Barreiro, 2007; Naghshtabrizi, Hespanha, & Teel, 2008; van de Wouw, Naghshtabrizi, Cloosterman, & Hespanha, 2009), linear dynamic controllers (Donkers, Heemels, van de Wouw, & Hetel, 2011; Walsh, Ye, & Bushnell, 2002), nonlinear dynamic controllers (Bauer, Maas, & Heemels, 2012; Heemels, Teel, van de Wouw, & Nešić, 2010; Nešić & Teel, 2004) and observer-based controllers (Montestruque & Antsaklis, 2004). However, results on controller synthesis for NCSs are rare (Hespanha, Naghshtabrizi, & Xu, 2007). LMI conditions for synthesis of state feedback (Cloosterman et al., 2010) and static output-feedback (Hao & Zhao, 2010) only became available recently. For general linear dynamic controller synthesis, (Dačić & Nešić, 2007) considered the simultaneous design of the protocol, without considering time-varying transmission intervals or delays, and resulted in a linearized BMI algorithm. General linear dynamic controller synthesis conditions were also formulated in Gao, Meng, Chen, and Lam (2010), where the NCS included quantization, delay and packet dropout but without a shared communication medium, which resulted in LMI conditions only when a specific design variable (ϵ in Gao et al. (2010)) is fixed. Synthesis conditions for observer gains that stabilize the state estimation error (but not the state of the plant itself) in the presence of a shared communication medium were given in Dačić and Nešić (2008). The inclusion of varying transmission intervals were recently presented in Postoyan and Nešić (2010). In Zhang and Hristu-Varsakelis (2006), Gramian-based tools were used to synthesize observer-based gains that stabilize the closed-loop in the presence of a shared communication medium but they did not consider time-varying transmission intervals nor delays. Conditions for observer-based controller synthesis in the presence of time-varying delay, time-varying transmission intervals, and dropouts were given in Naghshtabrizi and Hespanha (2005). The synthesis conditions were derived by changing a non-convex feasibility problem into a linear minimization problem via a linear cone complementarity algorithm. It is worth mentioning that all the aforementioned NCS results consider the *centralized* controller problem setting.

To summarize, we note that although a decentralized observer-based control structure is reasonable to use in practice, its design is extremely complex due to the fact that we simultaneously face the issues of (i) a decentralized control structure, (ii) limited measurement information and (iii) communication side-effects. In this context, the contribution of this paper is twofold: firstly, a model describing the controller decentralization and the communication side-effects is derived, and, secondly, the most significant contribution is LMI-based synthesis conditions for decentralized switched observer-based controllers and decentralized switched static feedback controllers, which are robust to communication imperfections. For the simpler case of static output feedback, we refer the reader to Bauer, Donkers, van de Wouw, and Heemels (2012).

1.1. Nomenclature

The following notation will be used. $\text{diag}(A_1, \ldots, A_N)$ denotes a block-diagonal matrix with the matrices $A_1, \ldots, A_N$ on the diagonal and $A^\top \in \mathbb{R}^{m\times n}$ denotes the transpose of the matrix $A \in \mathbb{R}^{n\times m}$. For a vector $x \in \mathbb{R}^n$, $\|x\| := \sqrt{x^\top x}$ denotes its Euclidean norm. We denote by $\|A\| := \sqrt{\lambda_{\max}(A^\top A)}$ the spectral norm of a matrix A, which is the square-root of the maximum eigenvalue of the matrix $A^\top A$. For brevity, we sometimes write symmetric matrices of the form $\begin{bmatrix} A & B \\ B^\top & C \end{bmatrix}$ as $\begin{bmatrix} A & B \\ \star & C \end{bmatrix}$. For a matrix $A \in \mathbb{R}^{n\times m}$ and two subsets $\mathbf{I} \subseteq \{1, \ldots, n\}$ and $\mathbf{J} \subseteq \{1, \ldots, m\}$, the $(\mathbf{I}, \mathbf{J})$-submatrix of A is defined as $(A)_{\mathbf{I},\mathbf{J}} := (a_{ij})_{i\in\mathbf{I}, j\in\mathbf{J}}$. In case $\mathbf{I} = \{1, \ldots, n\}$, we also write $(A)_{\bullet,\mathbf{J}}$.

2. The model and problem definition

We consider a collection of coupled continuous-time linear subsystems $\mathcal{P}_1, \ldots, \mathcal{P}_N$ given by

$$\mathcal{P}_i : \begin{cases} \dot{x}_i(t) = A_i x_i(t) + B_i \hat{u}_i(t) \\ \qquad + \displaystyle\sum_{\substack{j=1 \\ j\neq i}}^{N} \left(A_{i,j} x_j(t) + B_{i,j} \hat{u}_j(t)\right), \\ y_i(t) = C_i x_i(t) + \displaystyle\sum_{\substack{j=1 \\ j\neq i}}^{N} C_{i,j} x_j(t), \end{cases} \tag{1}$$