Automatica 49 (2013) 338–348

Contents lists available at SciVerse ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

A small gain framework for networked cooperative force-reflecting teleoperation[☆]

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ARTICLE INFO

Article history:
Received 25 November 2010
Received in revised form
3 May 2012
Accepted 27 August 2012
Available online 1 December 2012

Keywords:
Nonlinear systems
Teleoperation
Stability analysis
Communication networks
Large-scale systems

ABSTRACT

For cooperative force-reflecting teleoperation over networks, conventional passivity-based approaches have limited applicability due to nonpassive slave–slave interactions and irregular communication delays imposed by networks. In this paper, a small gain framework for stability analysis design of cooperative network-based force reflecting teleoperator systems is developed. The framework is based on a version of weak input-to-output practical stability (WIOPS) nonlinear small gain theorem that is applicable to stability analysis of large-scale network-based interconnections. Based on this result, we design a cooperative force-reflecting teleoperator system which is guaranteed to be stable in the presence of multiple network-induced communication constraints by appropriate adjustment of local control gains and/or force-reflection gains. Experimental results are presented that confirm the validity of the proposed approach.

1. Introduction

Teleoperation over communication networks has recently attracted significant attention due to its high flexibility, accessibility, and relatively low cost (Goldberg & Siegwart, 2002). The primary purpose of teleoperator systems is to make it possible for a human operator to execute a manipulation task remotely. A typical networked teleoperator system consists of two (or more) manipulators, called master(s) and slave(s), that are connected through a communication network. The master manipulator is manually controlled by the human operator, while the slave executes the task by following the motion of the master. In order to let the human operator feel the interaction with the task, the haptic data (slave positions/velocities as well as the interaction forces between the slave and the environment) can be transmitted back to the master site and displayed to the human operator through some sort of haptic interface. The theory and design of the networked master–slave teleoperator system has become an increasingly active research area in recent years, with a large and growing number of applications including telemedicine, telesurgery and collaborative surgery, telemaintenance, teleassistance for disabled, applications to education, entertainment, and many others. For an excellent account of the recent developments, please refer to the survey papers (Hokayem & Spong, 2006; Nuño, Basañez, & Ortega, 2011), where the former gives an overview of some recent contributions put in historical perspective, while the latter presents a number of teleoperation control schemes within a unifying passivity-based framework. For information on the theory and applications of the networked (in particular, Internet-based) teleoperators, the reader is referred to Ferre, Buss, Aracil, Melchiorri, and Balaguer (2007) and Goldberg and Siegwart (2002); see also Hokayem and Spong (2006, Section 3.7).

In cooperative teleoperator systems, multiple teleoperators perform tasks on the same environment (Sirouspour, 2005; Wang, Moallem, & Patel, 2003). Cooperative teleoperation enables collaboration between human operators that are geographically separated, and may lead to drastic improvement in handling capabilities, dexterity, as well as task completion time. Typical examples of applications include different assembly tasks, handling of toxic/radioactive materials and collaborative telesurgery. A structure of cooperative network-based teleoperator system is shown in

☆ The work of I.G. Polushin was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada under Grant RGPIN1510. The work of S.N. Dashkovskiy was supported by the German Research Foundation (DFG) as a part of the Collaborative Research Center 637 and partially by the grant number DA 767/3-1. The work of R.V. Patel was supported by NSERC under Grant RGPIN1345. The material in this paper was partially presented at the 8th IFAC Symposium on Nonlinear Control Systems NOLCOS 2010, September 1–3, 2010, Bologna, Italy. This paper was recommended for publication in revised form by Associate Editor Antonio Loria under the direction of Editor Andrew R. Teel. A. Takhmar received financial support from the NSERC Collaborative Research and Training Experience (CREATE) program in Computer-Assisted Medical Interventions.

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doi:10.1016/j.automatica.2012.11.001

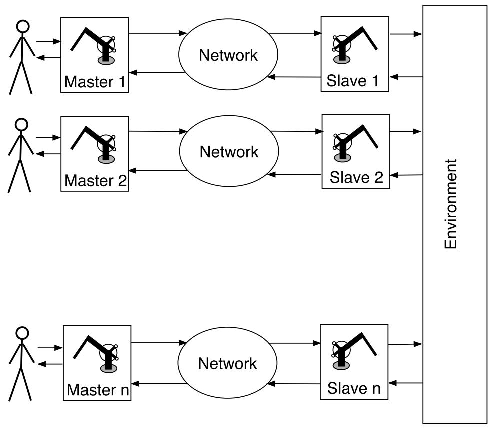

Fig. 1. A cooperative network-based teleoperator system.

Fig. 1. Specific features that makes such a system difficult for analysis and control design include multiple networked communication channels between the masters and the corresponding slaves, and the possibility of the slave–slave interactions through the common environment which may become non-passive if the slaves have different size. These features limit the applicability of the conventional passivity-based approaches (that typically involve different forms of scattering transformations or wave variables (Anderson & Spong, 1989; Lee & Spong, 2006; Niemeyer & Slotine, 2004)) for the design of such systems. In fact, there exists only a few works that deal with stability analysis of cooperative force reflecting teleoperator systems with communication constraints. Recent works on this topic include Bacocco and Melchiorri (2009) and Setoodeh, Sirouspour, and Shahdi (2006). In Setoodeh et al. (2006), the stability analysis is intrinsically linear, the communication delays are assumed to be constant and known, and the communication errors are not permitted; moreover, apparently the approach of Setoodeh et al. (2006) cannot be extended to the case of nonlinear systems or irregular unknown communication delays and communication errors. In Bacocco and Melchiorri (2009), the passivity & wave variables approach is employed; however, this work does not contain rigorous stability analysis, the communication delay are assumed to be constant, and no communication errors are admitted.

In this paper, we develop a framework for the design of bilateral cooperative teleoperators with network-induced communication constraints that is based on the small-gain arguments. Along with passivity theorems (Arcak & Sontag, 2006; Hill & Moylan, 1977), the small-gain theorems are among the most powerful tools in analysis and control of interconnected nonlinear systems (Jiang, 2004). However, the small-gain ideas have not yet been applied to the design of cooperative network-based teleoperator systems, which can probably be attributed to a number of difficulties associated with such an application. First, a cooperative teleoperator system can consist of multiple master–slave pairs that interact through environment, which generally results in an interconnection structure more complex than simple feedback interconnections to which the small-gain arguments are traditionally applied. Second, communication over networks imposes communication constraints that include time-varying discontinuous possibly unbounded communication delays and possible packet losses. Also, in robotic systems, stability with prescribed gains usually cannot be achieved globally, which implies that an appropriate version of the small-gain theorem must admit stability properties of subsystems to be satisfied within a compact subset of the state space and a compact range of inputs rather than globally (which corresponds to stability with finite restrictions as well as a bounded domain of small-gain conditions). Although a number of nonlinear small-gain theorems presented in the literature addressed some of the above mentioned issues (see, for example, Dashkovskiy, Rüffer, & Wirth, 2007, 2010; Karafyllis & Jiang, 2009; Tiwari, Wang, & Jiang, 2009 for small gain conditions for interconnection of multiple subsystems, Tiwari et al., 2009 for the case of bounded communication delays, Polushin, Marquez, Tayebi, & Liu, 2009; Rüffer, Sailer, & Wirth, 2010 for the case of discontinuous time-varying unbounded communication delays, and Polushin et al., 2009; Rüffer et al., 2010; Teel, 1996 for the case of finite restrictions), no small-gain results exist that would directly fit the specific requirements of the networked cooperative bilateral teleoperator systems. In this work, we first formulate and prove a new version of the weak input-to-output practical stability (WIOPS) small gain theorem that is applicable to stability analysis of large-scale network-based interconnections where the subsystems are assumed to satisfy the WIOPS property. Based on this result, we present a design of a cooperative networked force-reflecting teleoperator system with a typical interconnection structure. More specifically, using the developed multi-channel small-gain approach, we design a cooperative force-reflecting teleoperator system which is guaranteed to be stable in the presence of multiple network-induced communication constraints by appropriate adjustment of local control gains and/or force-reflection gains. Theoretical developments presented in this paper are supported by experiments. To the best of our knowledge, this is the first work where the small gain approach is applied to analyze stability of a networked cooperative force reflecting teleoperator system.

The organization of this paper is as follows. In Section 2, we formulate and prove a new version of the WIOPS small gain theorem that meets the specific requirements of networked force-reflecting cooperative teleoperator systems. In Section 3, we design a force-reflecting cooperative teleoperator system using the small-gain framework, and show that the system is stable in the presence of irregular communications. Experimental results are discussed in Section 4, and concluding remarks are given in Section 5.

2. The small gain theorem for network-based interconnections

2.1. Preliminaries

Throughout the paper, the following standard notation is used. Let $\mathbb{R}_+$ be the set of nonnegative real numbers, $\mathbb{R}_+ := [0, +\infty)$. A continuous function $\gamma : \mathbb{R}_+ \to \mathbb{R}_+$ is said to belong to class $\mathcal{G}$ ($\gamma \in \mathcal{G}$) if it is strictly increasing; a function $\gamma \in \mathcal{G}$ belongs to class $\mathcal{K}$ ($\gamma \in \mathcal{K}$) if it satisfies $\gamma(0) = 0$; a function $\gamma \in \mathcal{K}$ belongs to class $\mathcal{K}_\infty$ if $\gamma(s) \to \infty$ as $s \to \infty$. Also, we will occasionally use the notation $\mathcal{K}_{lin}$ to denote a subclass of $\mathcal{K}_\infty$ which consists of linear functions of the form $\gamma(s) := g \cdot s$, where $g > 0$. Finally, let us formally introduce a class of zero functions $\mathcal{O}$ which consists of a single element, *i.e.*, $\gamma \in \mathcal{O}$ if $\gamma(s) \equiv 0$ for all $s \in \mathbb{R}_+$.

When analyzing stability of cooperative teleoperator systems, one deals with multiple inputs–multiple outputs (MIMO) systems where each input–output pair has a specific gain function associated with it. For simplicity of notation in the MIMO case, it is convenient to use multivariable extensions of the classes $\mathcal{G}$, $\mathcal{K}$, $\mathcal{K}_\infty$, $\mathcal{K}_{lin}$, defined as follows. Let $\mathbb{R}^n_+$ be the positive orthant in $\mathbb{R}^n$, *i.e.*, $\mathbb{R}^n_+ := \{x \in \mathbb{R}^n, x_i \geq 0 \text{ for all } i = 1, \dots, n\}$. Given a set $\Gamma_{ij} : \mathbb{R}_+ \to \mathbb{R}_+$, $i \in \{1, \dots, n\}$, $j \in \{1, \dots, m\}$, consider an associated map $\Gamma : \mathbb{R}^m_+ \to \mathbb{R}^n_+$ defined according to the formula $\Gamma(s) = [(\Gamma(s))_1, \dots, (\Gamma(s))_n]$, where

$$(\Gamma(s))_i := \max_{j \in \{1,\dots,m\}} \Gamma_{ij}(s_j).$$

A map $\Gamma : \mathbb{R}^m_+ \to \mathbb{R}^n_+$ is said to belong to class $\mathcal{G}^{n\times m}$ if and only if it can be associated with a set $\{\Gamma_{ij}\}$, $i \in \{1, \dots, n\}$, $j \in \{1, \dots, m\}$, where all $\Gamma_{ij} \in \{\mathcal{G} \cup \mathcal{O}\}$. Classes $\mathcal{K}^{n\times m}$, $\mathcal{K}^{n\times m}_\infty$, and $\mathcal{K}^{n\times m}_{lin}$ are defined analogously.