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Nonlinear trilateral teleoperation stability analysis subjected to time-varying delays

Farzad Hashemzadeh [a,b,*], Mojtaba Sharifi [b,c], Mahdi Tavakoli [b]

[a] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
[b] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Canada
[c] Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

A trilateral teleoperation system facilitates the collaboration of two users to share control of a single robot in a remote environment. While various applications of shared-control trilateral haptic teleoperation systems have recently emerged, they have mostly been studied in the context of single-DOF, LTI robotic systems. On the other hand, robotic manipulators with multiple degrees of freedom (DOF) and therefore nonlinear dynamics have recently found many applications such as in robotic-assisted surgery and therapy, space exploration and navigation systems. In this paper, considering the full nonlinear dynamical models of multi-DOF robots, stability analysis of a dual-user haptic teleoperation system is considered over a communication network subjected to asymmetrical time varying delays and through a dominance factor suitable for trainer–trainee applications. Stability in free motion and contact motion and asymptotic position tracking of the trilateral haptic teleoperation system in free motion are proven via Lyapunov stability analysis and Barbalat's lemma where operators and the environment are assumed to be passive. Simulation and experimental results concerning robot position tracking and user-perceived forces for three 2-DOF robots and experimental analysis of user-perceived stiffnesses for three 3-DOF robots validate the theoretical findings pertaining to the system stability and demonstrate the efficiency of the proposed controller.

1. Introduction

One of the emerging applications of haptics and teleoperation involves trilateral systems in which two users collaborate in performing a task using a robot while receiving haptic feedback. Examples of these applications are in haptics-assisted surgical training (Chebbi, Lazaroff, & Liu, 2007; Greer, Newhook, & Sutherland, 2008; Nudehi, Mukherjee, & Ghodoussi, 2005) and robot-assisted rehabilitation (Culmer et al., 2010; Carignan & Olsson, 2004; Gupta & OMalley, 2006; Mussa-Ivaldi & Patton, 2000). The challenge of controller design for such systems is in guaranteeing the system stability at the same time as enhancing the effectiveness of collaboration by enabling the trainer to transfer/retract partial or full task authority to/from the trainee in a natural and intuitive way.

Robotic manipulators with multiple DOFs are ubiquitous in various applications and inevitably involve nonlinear dynamics. In past research, it is assumed that multi-DOF nonlinear robotic systems can be decoupled to 1-DOF systems for stability analysis of bilateral systems (Speich & Goldfarb, 2005). However, given model uncertainties and the fact that human operator(s) and environment(s) coupled to the haptic devices are also often multi-DOF nonlinear systems, full decoupling is next to impossible.

A shared control architecture for haptics-assisted training in minimally invasive surgery is proposed in Nudehi et al. (2005) in which 1-DOF LTI models for robots are assumed. A six-channel, dual-user teleoperation system for interaction between the users through a dominance factor is proposed in Khademian and Hashtrudi-Zaad (2012) in which the robots dynamical models are again 1-DOF LTI and a new framework for the coupled stability analysis of linear dual-user teleoperation is considered in Razi and Hashtrudi-Zaad (2014). Haptic-enabled training approaches are discussed in Shahbazi and Atashzar (2013) and in Shahbazi, Atashzar, Talebi, and Patel (2012) for a 1-DOF LTI multi-master/single-slave system.

Considering linear dynamics for robots, the stability analysis of a trilateral haptic collaboration is studied in Li, Tavakoli, and Huanq (2013c) using extending the Llewellyn's criterion. The stability analysis of a trilateral teleoperation by splitting desired task between two master robots is considered in Li, Tavakoli, and

* Corresponding author. Tel.: +984133393751; fax: +984133300819.
E-mail addresses: hashemzadeh@tabrizu.ac.ir (F. Hashemzadeh), sharifi3@ualberta.ca (M. Sharifi), mahdi.tavakoli@ualberta.ca (M. Tavakoli).

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Huanq (2013b). Conservatism analysis between absolute stability and passivity criteria in linear trilateral teleoperation is studied in Li, Tavakoli, Mendez, and Huang (2013d) and extension of the Zeheb–Walach absolute stability criteria for n-port networks is considered in Razi and Hashtrudi-Zaad (2012) that can be applied to linear trilateral teleoperation. Controller synthesis in a bilateral teleoperation of a composed system with single local manipulator and multiple cooperative remote manipulators are considered in Aldana, Nuno, and Basanez (2012) and trilateral teleoperation control of kinematically redundant robotic manipulators is studied in Malysz and Sirouspour (2011).

As far as LTI trilateral haptic systems are concerned, two different ways to study the stability are passivity (Mendez & Tavakoli, 2010; Panzirsch et al., 2012; Raisbeck, 1954; Shahbazi, Talebi, & Yazdanpanah, 2010) and absolute stability. Our research group has introduced an extension of Llewellyn's criterion for absolute stability analysis of single-DOF, LTI bilateral haptic systems to single-DOF, LTI trilateral haptic systems (Li, Tavakoli, & Huang, 2013a). We have also performed other extensions of the stability analysis to 3-DOF, LTI bilateral systems and to the more general case of multi-DOF multi-lateral LTI systems (Li, Tavakoli, & Huang, 2014). All of the above have been done in the context of LTI systems.

Design of stable and high-performance trilateral teleoperation systems involving robots with multi-DOF nonlinear dynamics has not received much attention yet. Time-varying time delays add to the complexity of the problem. In the literature of bilateral teleoperation under nonlinear robot dynamics and time-varying delays, P+D and PD like controllers are used widely to guarantee asymptotic stability of the closed-loop systems and zero convergence of the tracking errors (Hua & Liu, 2010; Kim, Ji, & Ambike, 2005; Lee & Spong, 2006; Polushin, Liu, & Lung, 2008). A stability analysis of a bilateral teleoperation system with actuator saturation and nonlinear dynamical models for robots and time varying delays in communication channel was studied in Hashemzadeh, Hassanzadeh, and Tavakoli (2013). Extension of the above to trilateral nonlinear teleoperation systems subject to time-varying delays remains to be done.

In this paper, assuming the operators and environment are passive, a PD like controller to guarantee the stability of a trilateral dual-user system in the presence of multi-DOF nonlinear dynamics for all three robots and time-varying communication delays in all communication channels is proposed. The system has two master robots for the two users and one slave robot to perform the desired task on an environment. In the trilateral teleoperation system, the goal is that two users collaboratively control a robot in order to perform a task. Based on a Lyapunov stability analysis and using Barbalat's lemma, theorems are given to analyze the stability and asymptotic position tracking of the proposed trilateral system. Simulation and experimental results show the validity of the theoretical findings and the efficiency of the proposed controller.

The rest of the paper is organized as follows. In Section 2, mathematical preliminaries are stated. In Section 3, the proposed controller for delay-free nonlinear trilateral teleoperation is proposed. Section 4 studies the generalization of the proposed controller in the presence of time-varying delays. In Section 5, simulation and experimental results are provided followed by the conclusions in Section 6.

Notation. We denote the set of real numbers by $R = (-\infty, \infty)$, the set of positive real numbers by $R_{>0} = (0, \infty)$, and the set of nonnegative real numbers by $R_{\geq 0} = [0, -\infty)$. Also, $\| X \|_\infty$ and $\| X \|_2$ stand for the Euclidian $\infty - norm$ and $2 - norm$ of a vector $X \in R^{(n\times 1)}$, and $|X|$ denotes element-wise absolute value of the vector X. The L_∞ and L_2 norms of a time function f: $R_{\geq 0} \to R^{n\times 1}$ are shown as $\| f \|_{L_\infty} = sup_{t\in[0,\infty)} \| f(t) \|_\infty$ and $\| f \|_{L_2} = \sqrt{\int_a^b f(x)dx}$, respectively. The L_∞ and L_2 spaces are defined as the sets $\{f: R_{\geq 0} \to R^{n\times 1}, \| f \|_{L_\infty} < +\infty\}$ and $\{f: R_{\geq 0} \to R^{n\times 1}, \| f \|_{L_2} < +\infty\}$, respectively. For simplicity, we refer to $\| f \|_{L_\infty}$ as $\| f \|_\infty$ and to $\| f \|_{L_2}$ as $\| f \|_2$. We also simplify the notation $\lim_{t\to\infty} f(t) = 0$ to $f(t) \to 0$.

2. Preliminaries

Consider the n-DOF master 1, master 2 and slave robots to have the following nonlinear dynamics, respectively:

$$M_1\big(q_1(t)\big)\ddot{q}_1 + C_1\big(q_1(t), \dot{q}_1\big)\dot{q}_1 + G_1\big(q_1(t)\big) = \tau_1(t) - \tau_{h_1}(t) \tag{1}$$

$$M_2\big(q_2(t)\big)\ddot{q}_2 + C_2\big(q_2(t), \dot{q}_2\big)\dot{q}_2 + G_2\big(q_2(t)\big) = \tau_2(t) - \tau_{h_2}(t) \tag{2}$$

$$M_s\big(q_s(t)\big)\ddot{q}_s(t) + C_s\big(q_s(t), \dot{q}_s(t)\big)\dot{q}_s(t) + G_s\big(q_s(t)\big) = \tau_s(t) - \tau_e(t) \tag{3}$$

Here, q_i, $\dot{q}_i$ and $\ddot{q}_i \in R^{(n\times 1)}$ for $i \in \{1, 2, s\}$ are the joint positions, velocities and accelerations of master 1, master 2 and slave, respectively. Also, $M_i(q_i(t)) \in R^{(n\times n)}$, $C_i(q_i(t), \dot{q}_i(t)) \in R^{(n\times n)}$, and $G_i(q_i(t)) \in R^{(n\times 1)}$ are the inertia matrices, the Coriolis/centrifugal matrices, and the gravitational vectors for the three robots. Moreover, τ_{h_1}, τ_{h_2} and $\tau_e \in R^{(n\times 1)}$ are the torques applied by the first and second human operators and the environment on their respective robots, respectively. Lastly, τ_1, τ_2 and $\tau_s \in R^{(n\times 1)}$ are the control signals (torques) for the master 1, master 2 and the slave robots, respectively. Properties of the nonlinear dynamic models (1)–(3), which will be used in this paper, are (Kelly, Davila, & Perez, 2006; Spong, Hutchinson, & Vidyasagar, 2006):

1. For a manipulator with revolute joints, the inertia matrix $M(q)$ is symmetric positive-definite and has the following upper and lower bounds:

   $$0 < \lambda_{min}\big(M\big(q(t)\big)\big)I \leq M\big(q(t)\big) \leq \lambda_{Max}\big(M\big(q(t)\big)\big)I \leq \infty$$

   where $I \in R^{(n\times n)}$ is the identity matrix and λ denotes the eigenvalue of a matrix.
2. For a manipulator, the relation between the Coriolis/centrifugal and the inertia matrices is as follows:

   $$\dot{M}\big(q(t)\big) = C\big(q(t), \dot{q}(t)\big) + C^T\big(q(t), \dot{q}(t)\big)$$

   This is equivalent to $\dot{M}\big(q(t)\big) - 2C\big(q(t), \dot{q}(t)\big)$ being skew-symmetric.
3. For a manipulator with revolute joints, there exists a positive bounding the Coriolis/centrifugal term as follows:

   $$\| C\big(q(t), x(t)\big)y(t)\|_2 \leq \| x(t)\|_2 \| y(t)\|_2$$
4. The time derivative of $C\big(q(t), \dot{q}(t)\big)$ is bounded if $\dot{q}(t)$ and $\ddot{q}(t)$ are bounded.

3. Proposed trilateral teleoperation laws

As described before, a dual-user teleoperation system comprises two master robots as haptic interfaces for the two users and one slave robot to perform a desired task on an environment. This finds application in many real-world scenarios such as when the