ISA Transactions 52 (2013) 268–277

Contents lists available at SciVerse ScienceDirect

ISA Transactions

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

Research Article

A novel control framework for nonlinear time-delayed Dual-master/Single-slave teleoperation

A. Ghorbanian [a,*], S.M. Rezaei [a,b], A.R. Khoogar [c], M. Zareinejad [b], K. Baghestan [a]

[a] Department of Mechanical Engineering, AmirKabir University of Technology, Tehran, Iran
[b] New Technologies Research Centre, Amirkabir University, Tehran, Iran
[c] Department of Mechanical and Aerospace Engineering, Science and Research branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

Article history:
Received 26 April 2012
Received in revised form
9 July 2012
Accepted 12 September 2012
Available online 9 November 2012

Keywords:
Teleoperation
Dual-master/Single-slave system
Stability
Variable time-delay

ABSTRACT

A novel trilateral control architecture for the Dual-master/Single-slave teleoperation is proposed in this paper. This framework has been used in surgical training and rehabilitation applications. In this structure, the slave motion has been controlled by weighted summation of signals transmitted by the operator referring to task control authority through the dominance factors.

The nonlinear dynamics for telemanipulators are considered which were considered as disregarded issues in previous studies of this field. Bounded variable time-delay has been considered which affects the transmitted signals in the communication channels. Two types of controllers have been offered and an appropriate stability analysis for each controller has been demonstrated. The first controller includes Proportional with dissipative gains ($P+d$). The second one contains Proportional and Derivative with dissipative gains ($PD+d$). In both cases, the stability of the trilateral control framework is preserved by choosing appropriate controller's gains. It is shown that these controllers attempt to coordinate the positions of telemanipulators in the free motion condition. The stability of the Dual-master/Single-slave teleoperation has been proved by an appropriate Lyapunov like function and the stability conditions have been studied. In addition the proposed $PD+d$ control architecture is modified for trilateral teleoperation with internet communication between telemanipulators that caused such communication complications as packet loss, data duplication and swapping. A number of experiments have been conducted with various levels of dominance factor to validate the effectiveness of the new control architecture.

1. Introduction

Teleoperated systems have significant developments in various applications such as surgery, space technology, underwater exploration, surgical training, etc. [1]. Teleoperation provides a safe interaction between the operator and the environment that are probably located far from each other. From number of teleoperators point of view, the teleoperated systems are divided into two general categories: the bilateral and the multilateral teleoperation.

In the bilateral teleoperation, the master and the slave robots interact with each other through communication channels between the local and the remote sites. Over last decades there have been significant developments to control the bilateral teleoperated systems [2]. Furthermore, many investigations have been carried out on various aspects of bilateral teleoperation such as transition process of contact to environment [3], and fuzzy control has been for teleoperated systems [4], bilateral control over stochastic and time-varying delay [5], macro–micro teleoperation and cell manipulation [6].

Several applications, including rehabilitation [7], surgical training and signal modification [8,9] require multiple users instead of single operator to control the slave motion. Moreover, multilateral teleoperation provides various capabilities such as increased dexterity, improved loading and handling capacity etc. One of the applied fields of multilateral teleoperation includes Dual-master/Single-slave that is used in surgical training and rehabilitation. In this field, two masters cooperatively control the slave robot to perform a special task on the environment. The authority over the slave motion is shared between the operators by means of dominance factor.

Khademian and Hashtrudizaad proposed a four-channel controller for Dual-master/Single-slave teleoperation [10]. To study the stability of system, linear impedance models for telemanipulators and environment were considered and the communication

* Corresponding author.
E-mail addresses: a.ghorbanian@aut.ac.ir (A. Ghorbanian), smrezaei@aut.ac.ir (S.M. Rezaei), Khoogar@gmail.com (A.R. Khoogar), mzare@aut.ac.ir (M. Zareinejad), k_baghestan@aut.ac.ir (K. Baghestan).

0019-0578/$ - see front matter © 2012 ISA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.isatra.2012.09.003

delays were ignored. The Llewellyn's criterion was employed to analyze the stability of trilateral teleoperation. It is shown that optimized controller gains can be chosen to preserve the stability with satisfactory transparency of system [11].

Sirouspour proposed a new μ-synthesis based robust control architecture for Multi-master/Multi-slave teleoperation. In this architecture, the impedance models for the masters, slaves, operators and environment were considered to study the stability of system [12]. Furthermore, in the proposed four-channel control framework, the position and force information were shared between all masters and slaves. Subsequently, Sirouspour and Setoodeh extended the bilateral nonlinear adaptive control architecture that was proposed earlier for multilateral teleoperation systems [13,14]. This position based control architecture guarantees the stability of the multilateral teleoperation. Moghimi and Sirouspour used the proposed adaptive controller for collaborative haptic training [15]. However, in this control architecture the authority of masters was assumed to be equivalent over the slave. Malysz and Sirouspour proposed a new architecture to control a redundant slave manipulator by using dual masters [16]. However, the masters performed separated control tasks on the slave motion in contrary to common incorporative dual-user systems.

The most important complications in teleoperated systems are the stability of the system against dynamic nonlinearities of the telemanipulators and the environment as well as the delays in the communication channels. However in all above control architectures, the communication time-delays were ignored and in the most cases, the manipulators, environment and operators were assumed as impedance elements [11,12]. Therefore, designing a control framework which preserves stability of system against these complications is much desired for researchers.

The main contribution of this paper includes a new trilateral control architecture that provides a direct interaction between the users and the slave in the application of surgical training. Transmitted position signals are exchanged between the masters and slave, based on task control authority through the dominance factors. The authority of the trainer over the trainee and the slave is determined by means of dominance factors α and β respectively. The dominance factor β causes the supremacy of trainer over the slave to become more than the supremacy of trainer over the trainee when the first dominance factor, α, varies between 0.5 and 1 (the trainee is amateur to control the slave solitarily). The nonlinear dynamics for manipulators are considered, indeed, we have supposed bounded time-varying delays affect the transmitted signals in the communication channels. Two types of controllers have been proposed for each telemanipulators. In the first case; the controller is proportional to position error of manipulators with a dissipative term $(P+d)$ that is commonly used for conventional Single-master/Single-slave teleoperation [17]. However, the second proposed controller contains the Proportional and Derivative with dissipative gains $(PD+d)$, that is employed in such bilateral control architectures [18–20]. Lee and Spong employed the close loop energetic passivity to study the stability of Single-master/Single-slave teleoperated systems with constant delay [21] and the Lyapunov stability in bilateral teleoperation with constant delay was developed by Chopra and et al. [22] for the case of PD controller. However the stability of proposed trilateral control architecture is proved by opting proper gains for controllers referring to known upper bound of delay between telemanipulators. Two Lyapunov like functions are suggested for each controller to prove the stability of Dual-master/Single-slave teleoperation. Furthermore it is shown that in free motion, the position of slave converges to the masters' position signals based on control authority factor β. Moreover, it is demonstrated that the force has been reflected between operators, proportional to the control authority of users (α). Furthermore, a new controller has been designed for internet communication with discrete-time channels between telemanipulators that includes such communication unreliability as packet loss, data duplication and swapping.

2. Dual-master/Single-slave teleoperation configuration

Dual-master/Single-slave systems include two users that try to control the slave robot on the remote place by means of corresponding master robots, cooperatively. In these systems, the authority of the masters over the slave is determined by dominance factor. The telemanipulators are connected to each other through communication channels. However, when the telemanipulators were located far from each other, the delays in the communication channels affect the stability of system. In this architecture all transmitted signals has been shared between telemanipulators. Thus the local controllers of robots provide an appropriate control signal that compensates the operators and slave motion (Fig. 1).

2.1. Training strategy

We define two dominance factors α and β such that $0 \le \alpha, \beta \le 1$. The α factor determines the authority of trainer over trainee and $1-\alpha$ implies the supremacy of trainee over trainer. Moreover the dominance factors β and $1-\beta$ indicate the supremacy of trainer and trainee over the slave robot, respectively. When $\alpha=\beta=1$ the supremacy of trainee over the slave tends to zero and the slave's motion is controlled by trainer directly. Furthermore the controller of trainee efforts him/her to follow the trainer's motion. The training procedure is divided into two

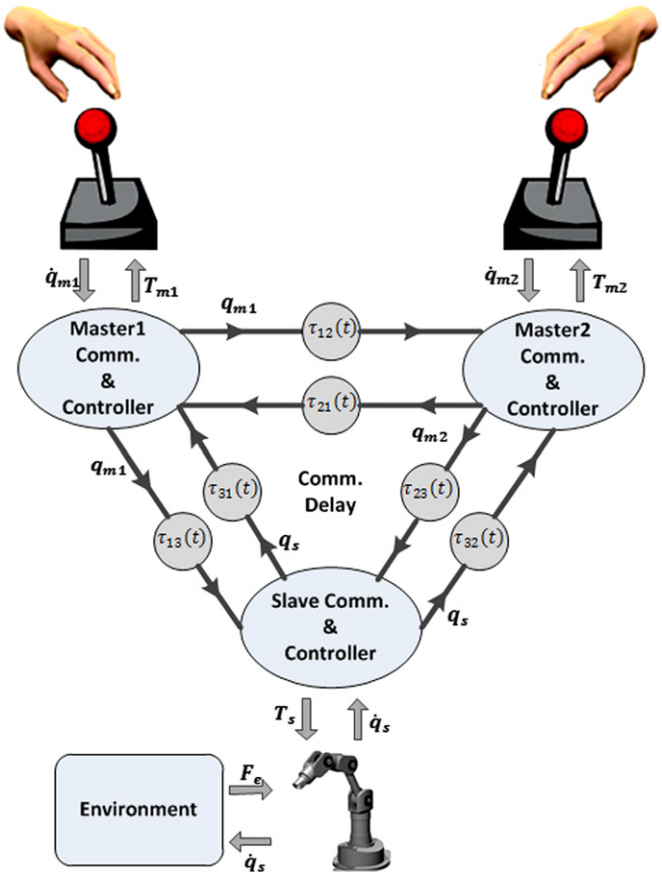

Fig. 1. Dual-master/Single-slave trilateral teleoperation.