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Research article

Dual-user nonlinear teleoperation subjected to varying time delay and bounded inputs

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ABSTRACT

A novel trilateral control architecture for Dual-master/Single-slave teleoperation system with taking account of saturation in actuators, nonlinear dynamics for telemanipulators and bounded varying time delay which affects the transmitted signals in the communication channels, is proposed in this paper. In this research, we will address the stability and desired position coordination problem of trilateral teleoperation system by extension of (nP+D) controller that is used for Single-master/Single-slave teleoperation system. Our proposed controller is weighted summation of nonlinear Proportional plus Damping (nP+D) controller that incorporate gravity compensation and the weights are specified by the dominance factor, which determines the supremacy of each user over the slave robot and over the other user. The asymptotic stability of closed loop dynamics is studied using Lyapunov-Krasovskii functional under conditions on the controller parameters, the actuator saturation characteristics and the maximum values of varying time delays. It is shown that these controllers satisfy the desired position coordination problem in free motion condition. To show the effectiveness of the proposed method, a number of simulations have been conducted on a varying time delay Dual-master/Single-slave teleoperation system using 3-DOF planar robots for each telemanipulator subjected to actuator saturation.

1. Introduction

A bilateral teleoperation system is composed of master and slave robots, where the signals are exchaned between the two robots via a communication channel. On being manipulated by a human operator, the controlled coupling between the master and slave robots is utilized by the slave robot for carrying out tasks remotely. The main advantage of a teleoperation system is its capability to provide a safe interaction between the operator and the environment to accomplish tasks in remote and hazardous environments. The distance between the local and remote robots poses a inevitable time delay in the communication channel, which can destabilize the telerobatic. In practice, the communication delay can be time-varying and asymmetric in the forward and backward paths between the operator and the remote environment [1,2]. There are a number of control schemes for time-varying delay compensation in the literature [3,4]. Over last decades there have been significant developments to control the bilateral teleoperated systems [5]. Furthermore, many investigations have been carried out on various aspects of bilateral teleoperation [6–9].

From number of teleoperators point of view, the teleoperated systems fall into two main categories: the bilateral and the multilateral teleoperation. A conventional bilateral teleoperation system usually involves a single slave robot which is controlled by a single operator. However, it is more effective in many applications to have multiple manipulators in a teleoperation system. Multi robot systems have been extensively employed in the production processes such as manufacturing and automotive application (assembling, transporting, painting and welding), rehabilitation [10], surgical training [11] and signal modification [12]. Therefore, the multilateral teleoperation has been gradually becoming a popular topic and many approaches have been proposed such as H_∞ control [11] and adaptive control [13–15]. 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 [13]. 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 [14,15]. This position based control architecture guarantees the stability of the multilateral teleoperation.

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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 remote 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 [16]. To study the stability of system, linear impedance models for telemanipulators and environment were considered and the communication delays were ignored. The Llewellyns 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 [17]. Moghimi and Sirouspour used the proposed adaptive controller ([14,15]) for collaborative haptic training [18]. 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 [19]. 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. Ghorbanian et al. [20], proposed a new trilateral control architecture for Dual-master/Single slave teleoperation system regarding nonlinear dynamics and bounded variable time delay in communication channels.

On the other hand, in almost all applications of control systems including teleoperation systems, the actuator output (i.e., control signal) has a limited amplitude, i.e., is subject to saturation. Controllers that ignore actuator saturation may cause undesirable responses and even closed-loop instability [21]. Although it may be possible to avoid actuator saturation by using sufficiently high-torque actuators in robots, the large size of the actuators will cause further problems in robot design and control. Therefore, it is highly desirable to develop control methods that take any actuator saturation into account at the design outset and, therefore, allow for efficient and stable control with small-size actuators that inevitably possess a limited output capacity. In order to address the stability of the position control loop for a single robotic manipulator subjected to bounded actuator output, several approaches have been proposed in the literature. An anti-windup approach is presented to guarantee global asymptotic stability of Euler-Lagrange systems in [22]. A velocity and position feedback method with adaptive gravity compensation is reported in [23], in which the velocity and position errors separately pass through two nonlinear saturating functions and the outputs are then added to an adaptive gravity compensation term. In [24], a brief review of PD plus gravity compensation controllers is provided.

None of the above research has been done in the context of teleoperation systems. Going beyond anti-saturation control for a single robot, there has been some attention paid recently to actuator saturation in bilateral teleoperation systems [25]. Combining wave variable with a nonlinear proportional controller, an architecture to handle actuator saturation is discussed in [26], for the case where the delay in the communication channel is constant. In [27], an anti-windup approach combined with wave variables is used for constant-delay teleoperation subjected to bounded control signals. Hashemzadeh and et al. [28], proposed (nP+D) controller to deal with actuator saturation in Single-master/Single-slave teleoperation system. (nP+D) controller is similar to the proportional plus damping (P + D) controller [3], with the difference that it takes into account the actuator saturation at the outset of control design and alters the proportional term by passing it through a nonlinear function.

This paper addresses the stability and desired position coordination problem of Dual-master/Single-slave teleoperation system, considering nonlinear dynamics for telemanipulators, bounded varying time delay in transmitted signals and saturation in actuators. The proposed controller is weighted summation of nonlinear Proportional plus Damping (nP+D) controller that incorporate gravity compensation and the weights are specified by the dominance factor, which determines the supremacy of each user over the slave robot and over the other user. By employing Lyapunov-Krasovskii functional we establish the relationships among the controller-design parameters and the upper bounds of the time-varying delays.

This paper is organized as follows. Section 2 states the preliminaries while proposed controller and the stability analysis are in Section 3 and 4 respectively. In Section 5, simulation results are shown and discussed. In Section 6 conclusions are reported.

In this paper, 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 Euclidean ∞-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 $\|f\|_{L_\infty} = \sup_{t\in[0,\infty)} \left\|f(t)\right\|_\infty$ and $\|f\|_{L_2} = \sqrt{\int_0^\infty \left\|f(t)\right\|_2^2 dt}$, respectively. The L_∞ and L_2 spaces are defined as the sets of $\left\{f: R_{\geq 0} \to R^{n\times 1}, \|f\|_{L_\infty} < +\infty\right\}$ and $\left\{f: R_{\geq 0} \to R^{n\times 1}, \|f\|_{L_2} < +\infty\right\}$, 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

2.1. Problem formulation

with the assumption that manipulators in the teleoperation system are modeled by lagrangian systems and driven by actuated revolute joints, the dynamics of the Dual-master/Single-slave trilateral teleoperation system where actuators are subjected to saturation are given as

$$M_{m_1}\left(q_{m_1}(t)\right)\ddot{q}_{m_1}(t) + C_{m_1}\left(q_{m_1}(t), \dot{q}_{m_1}(t)\right)\dot{q}_{m_1}(t) + G_{m_1}\left(q_{m_1}(t)\right) = \tau_{h_1}(t) - S_{m_1}\left(\tau_{m_1}(t)\right) \quad (1)$$

$$M_{m_2}\left(q_{m_2}(t)\right)\ddot{q}_{m_2}(t) + C_{m_2}\left(q_{m_2}(t), \dot{q}_{m_2}(t)\right)\dot{q}_{m_2}(t) + G_{m_2}\left(q_{m_2}(t)\right) = \tau_{h_2}(t) - S_{m_2}\left(\tau_{m_2}(t)\right) \quad (2)$$

$$M_s\left(q_s(t)\right)\ddot{q}_s(t) + C_s\left(q_s(t), \dot{q}_s(t)\right)\dot{q}_s(t) + G_s\left(q_s(t)\right) = S_s\left(\tau_s(t)\right) - \tau_e(t) \quad (3)$$

For $k \in \{m_1, m_2, s\}$, $q_k(t)$, $\dot{q}_k(t)$ and $\ddot{q}_k(t) \in R^{n\times 1}$, are the vectors of the joint positions, velocities and accelerations of the master1 (m_1), master2 (m_2) and slave (s) robots respectively. Also $M_k(q_k(t)) \in R^{n\times n}$, $C_k\left(q_k(t), \dot{q}_k(t)\right) \in R^{n\times n}$ and $G_k\left(q_k(t)\right) \in R^{n\times 1}$ are the Inertia matrix, the Coriolis/centrifugal matrix, and the gravitational vector respectively. Moreover for $i \in \{1, 2\}$, $\tau_{h_i}(t) \in R^{n\times 1}$, are the first operator and the second operator applied torques on the corresponding robots. $\tau_e(t) \in R^{n\times 1}$ is the torque exerted by