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Position and force tracking in nonlinear teleoperation systems with sandwich linearity in actuators and time-varying delay

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ABSTRACT

In this paper, a new bounded force feedback control law is proposed to guarantee position and force tracking in nonlinear teleoperation systems in the presence of passive and nonpassive input interaction forces, time varying delay in their communication channels and sandwich linearity in their actuators. The proposed control is a nonlinear-proportional plus nonlinear damping *(nP+nD*) controller with the addition of a nonlinear function of the environment force on the slave side and nonlinear function of the human force and force error on the master side, the transparency of the proposed scheme will be improved. The controller prevents the inputs from reaching their usual actuator bounds. Using a novel Lyapunov–Krasovskii functional, the asymptotic stability and tracking performance of the teleoperation system are established under some conditions on the controller parameters, actuator saturation characteristics and maximum allowable time delays.

1. Introduction

Teleoperation systems enable humans to carry out tasks in remote or hazardous environments. Such remote systems have applications that include space and undersea exploration [1], robotic surgery [2] and handling of toxic and dangerous materials [3]. A typical teleoperation system is commonly made-up of the operator, the master robot, the communication channel, the slave robot, and the task environment. The operator's task performance in teleoperations is greatly improved if the haptic feedback about interaction occurring between the remote robot and the remote environment is provided to the human operator through the local robot. These teleoperation systems are called bilateral because information flows in two directions between the operator and the remote environment.

There are two main objectives in bilateral teleoperation. The first goal is that the slave robot tracks the position of the master robot and the other is that the operator should feel the environmental force when the slave contacts the remote environment; this objective is called transparency. In order to achieve transparency in bilateral teleoperation, the remote environment must provide information in different forms. These include audio, visual and tactile feedback through the feedback loop to the master side. The contact force feedback (haptic feedback) can provide a better sense of interaction with the remote environment, which generally improves the ability of the operator to perform more complex tasks. Nevertheless, the main control objective is stability. In fact, the main purpose is design of a stable control scheme for transmission of position, velocity and force signals from master robot to slave robot and vice versa.

Because of the significant distance between master and slave robot, time delays are unavoidable as data is transmitted between the local and remote sites. To reduce costs and increase global accessibility, teleoperation can be performed over internet

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communication lines rather than expensive, specially-designed telecommunication channels. The currently-available communication networks suffer from the unpredictable nature of the transmission delay associated with the data packets from local to remote and remote to local platforms. The data packet delays depend on the connection length of the hosts and the number of nodes. In practice, these transport delays can be time-varying and asymmetrical. The time delays can destabilize and degrade the tracking performance of closed-loop telerobotic systems if they are not well compensated [4–6]. Many control schemes have been proposed to compensate for time-delay [7–16].

In some of previous controllers for compensation of time-varying delays in teleoperation systems, derivatives of time delays $\dot{q}$ is required to be less than or equal to one and some of them also require the value of it, which is unknown in practical application. Thus, it is desirable to have a control scheme that allows $\dot{T}$ to take a bounded value.

Besides restrictive derivative time delays, most control schemes only ensure position tracking. In addition to position tracking, force tracking is critically important in teleoperation because this information helps arrive at decisions and results in more successful completion of a task. For example, in minimally-invasive surgery, to carry out safer and more delicate surgical tasks using robotic manipulators, accurate and reliable reproduction of the haptic sensations to the surgeon is essential [17–20].

Several approaches have been proposed to ensure stability and position and force tracking, but still have some of limitations. For instance, some studies have proposed controllers for force and position tracking in a nonlinear teleoperation system, but these controllers only work for slowly-varying delays [21–23].

Other control methods that ensure both position and force tracking are either for no-delay or constant-delay nonlinear teleoperation or for linear teleoperation [24–27].

In [28], authors proposed a novel control scheme to guarantee position and force tracking in nonlinear teleoperation systems subject to varying communication delays.

A common assumption in these controllers is that the actuators are able to provide any requested torque. In practice, robotic actuators have physical constraints that limit the amplitude of the available torques. Controllers that ignore these constraints may cause undesirable responses, thermal or mechanical failure and even closed-loop instability [29]. Therefore, it is necessary to develop control schemes that take actuator limits into account. Actuator constraints have been investigated in many references [30–36].

Going beyond these, some studies have attempted to cope with actuator saturation in bilateral teleoperation systems. authors in [37] proposed a nonlinear proportional controller combined with a wave variable scheme to deal with actuator saturation for bilateral teleoperation under a constant time delay. In [38], authors introduced an anti-windup approach combined with wave variables for constant-delay teleoperation subjected to bounded control signals. Hashemzadeh et al. [39] proposed a novel nonlinear proportional plus a damping controller for bilateral teleoperation systems under time-varying delays in their communication channel and actuator saturation. Using this control scheme, Zhai et al. [40] considered the control design problem for nonlinear teleoperation system in the presence of asymmetric time-varying delays and actuator saturation with no velocity measurement. Recently, a complete version of the method proposed in [37,38] was presented by Lee [41]. The authors extended analysis of the teleoperation scheme proposed by Chopra [42] to a case of input saturation and introduced a new control method that guarantees the stability of teleoperation systems under constant time delay. Yang et al. [43] designed a new an adaptive neural network (ANN) based prescribed performance control scheme for bilateral teleoperation systems with asymmetric constant time delays subject to system uncertainty and input saturation. Authors in [44] considered the unknown gravity term and proposed an output-feedback adaptive saturated-proportion plus saturated-damping (SP+Sd) controller based on the estimated velocity for a bilateral teleoperation system with time-varying delays and bounded inputs. Authors in [45] introduced a novel switching-based adaptive control scheme to cope with actuator saturation in nonlinear teleoperation systems with varying time delay, passive or nonpassive external force, dynamic uncertainty and disturbance.

These control schemes, however, ensure only stability and position synchronization for bilateral teleoperation system under input saturation.

Also, some of these control schemes are based on the strict assumption that the input interaction forces are passive. In reality, it is very difficult to satisfy passivity condition in bilateral teleoperation systems as slave interacts with uncertain remote environment which may not only be passive but also be nonpassive.

To the best of the author's knowledge, there are no studies on full transparency which measures in terms of position and force tracking performance in nonlinear teleoperation systems with asymmetric time-varying delays and actuator saturation.

The present study presents an extension of the controller proposed by Hashemzadeh et al. [39] to achieve transparency which measures in terms of position and force tracking performance in a nonlinear teleoperation system under three problems arising in practical applications of teleoperation systems: input saturation, asymmetrical time-varying communication delays with bounded rate of variation and nonpassive input forces, simultaneously. A novel bounded force feedback control law is proposed to overcome these limitations. Different from controller [39], the novel controller adds bounded force feedback terms to master and slave controller to improve transparency. Also we explore stability and position and force tracking performance under both passive and nonpassive/constant input force. The controller guarantees asymptotic stability, position and force tracking and prevents the inputs from reaching their usual actuator bounds.

The network is modeled as time varying and asymmetric delays. The proposed controller is a nonlinear-proportional plus nonlinear damping *(nP+nD)* controller with the addition of a nonlinear function of the environment force on the slave side and nonlinear function of the human force and force error on the master side. The controller has been introduced to improve transparency. A new Lyapunov-Krasovskii functional is employed to study the asymptotic stability, position and force tracking performance of the teleoperation system. The simulation results show the efficiency of the proposed method in tracking performance.