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A novel approach for stability and transparency control of nonlinear bilateral teleoperation system with time delays

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ABSTRACT

In this paper, a novel control approach is presented to improve the stability and transparency of the nonlinear bilateral teleoperation system with time delays, where a four-channel (4-CH) architecture using modified wave reflection reduction transformation is explored in order to guarantee the passivity of the communication channels in the nonlinear bilateral teleoperation system; a sliding-mode controller is proposed to compensate for the dynamic uncertainties and enhance the system synchronization performance in finite time. The system stability has been analyzed using Lyapunov functions. The proposed method is validated through experimental work based on a 3-DOF bilateral teleoperation platform in the presence of time delays. The experimental results clearly demonstrate that the proposed control algorithm has superiority on system transparency over other wave-based systems.

1. Introduction

A bilateral teleoperation system can extend human sensing, decision making and manipulative capabilities to a remote object and make the control system more flexible than a fully automated system. In a conventional bilateral teleoperation system, the master robot is driven by a human operator to command the slave robot to follow the master robot's motion and manipulate the remote environment. The force information produced during interaction between the slave robot and the environment is also fed back in order to haptically render the human operator's experience. The quality of such a system is primarily measured through the two critical indices of stability and transparency. The system stability requires the closed loop system to be stable under different environmental conditions. In a transparent system, the medium between the operator and the environment is not felt as the dynamics of the master and the slave are canceled out (Passenbarg et al., 2010; Chan et al., 2014). Since force feedback may cause instability, achieving a trade-off between stability and transparency is a challenge in bilateral teleoperation (Lawrence, 1992).

The system stability can be easily affected by time delays as a small time delay may result in an unstable system. Anderson and Spong propose a delay dependent controller for constant delays based on scattering theory (Anderson & Spong, 1989). Niemeyer and Slotine extend the scattering approach and introduce the wave variables concept (Niemeyer & Slotine, 1991). Based on this concept, many researchers suggest numerous new approaches to deal with time delays, which have been reviewed by a detailed survey (Sun et al., 2014). There are, however, two consistent problems with the wave variable including wave reflections and position drift particularly significant in hard environment contact or communication blackout.

Lee and Spong deploy direct position feedback with the prior knowledge of the time delays' upper bound to eliminate position drift (Lee & Spong, 2006). Nunõ et al. explore the stability of the nonlinear teleoperation system by using P-like, PD-like and scattering control methods under the classic assumptions of passivity (Nuño et al., 2008, 2009). Later, they introduce a general Lyapunov-like function to unify stability analysis on the passivity-based control for the nonlinear teleoperation system (Nuño et al., 2011). Chopra et al. propose the adaptive control laws based on the scattering approach to ensure position synchronization (Chopra et al., 2008). However, enhancing transparency of the wave-based system and simultaneously guaranteeing stability under time-varying delays still needs to further explore.

The contributions made by this paper address the challenges mentioned above: An innovative four-channel (4-CH) architecture applying the modified wave transformation is proposed to reduce the effects of wave reflections and to simultaneously guarantee the passivity of the communication channels. The stability of the nonlinear 4-CH teleoperation system is analyzed using Lyapunov functions. A sliding-mode control strategy is proposed to

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compensate for the dynamic uncertainties in order to enhance transparency and guarantee the system achieve stability and synchronization performance in finite time. The theoretical work presented here is supported by experimental results based on a 3-DOF master-slave teleoperation platform consisting of two haptic devices.

The remainder of the paper is structured as follows: After introducing the background on the passivity of the wave variable method and wave-variable-based reflections in Section 2, the proposed system will be described in Section 3. In this section the delay-based stability and the conditions for realizing transparency of the proposed system will be also studied. Results of the experimental work on different environment situations are presented in Section 4. Section 5 draws some conclusions.

2. Background

2.1. Passivity and wave variables

A standard wave-based teleoperation architecture is illustrated in Fig. 1. In such a system, a complementary pair of wave variables (u_m and v_s) are defined by the wave-encoding mechanism in terms of standard power signals (velocity $\dot{q}_i$ and force F_j) as (1). (i = m, s, m – master, s – slave; j = h, e, h – human, e – environment)

$$u_m = \frac{b\dot{q}_m + F_h}{\sqrt{2b}},\ v_s = \frac{b\dot{q}_s - F_e}{\sqrt{2b}} \tag{1}$$

In this relationship, b denotes the wave characteristic impedance, and u_m and v_s are the forward wave variables being transmitted from master to slave and the returning wave variable being transmitted from slave to master, respectively. The power flow is decoupled into the forward flow and the feedback flow as shown below:

$$\begin{aligned} P &= F_h(t)\dot{q}_m(t) - F_e(t)\dot{q}_s(t) \\ &= \frac{1}{2}\left(u_m^T(t)u_m(t) - v_m^T(t)v_m(t) + v_s^T(t)v_s(t) - u_s^T(t)u_s(t)\right) \end{aligned} \tag{2}$$

A system is passive if the output energy does not exceed the sum of the initial stored energy and the energy injected into the system (Spong et al., 2005). In the wave-based architecture, a system is passive when it satisfies the following condition:

$$\int_0^t \frac{1}{2}\left(v_s^T(t)v_s(t) - v_m^T(t)v_m(t)\right) \le \int_0^t \frac{1}{2}\left(u_m^T(t)u_m(t) - u_s^T(t)u_s(t)\right) + E_{store}(0), \forall t \ge 0 \tag{3}$$

where $E_{store}(0)$ denotes the initial energy stored in the system.

The passivity of a wave-based architecture can be analyzed using scattering theory. For a linear time invariant (LTI) two-port network where force vector $F = [F_h F_e]^T$ and velocity vector $\dot{q} = [\dot{q}_m \dot{q}_s]^T$, the scattering matrix can be expressed as:

$$F - \dot{q} = S(F + \dot{q}) \tag{4}$$

The necessary and sufficient condition for the passivity of a wave-based system is when the norm of scattering matrix S is less than or equal to 1 ($\|S\| \le 1$). In the case of a general two-port network, the passivity condition $\|S\| \le 1$ is a sufficient condition for absolute stability (Sun et al., 2014).

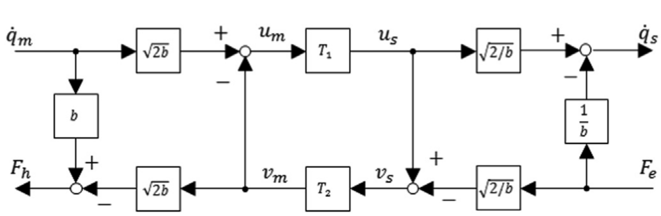

Fig. 1. Standard wave-based teleoperation architecture.

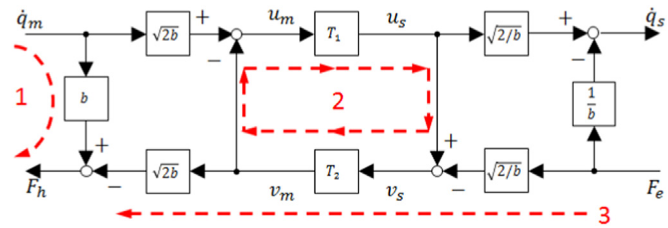

Fig. 2. Wave reflections.

2.2. Wave reflection

The phenomenon of wave reflection, caused by the imperfectly matched junction impedance in the wave-based system as shown in Fig. 2, was first observed by Niemeyer and Slotine (Niemeyer, 1996). The wave-based teleoperation system shown in Fig. 2 consists of three independent channels: the master's direct feedback (dotted line 1), the wave reflection (dotted line 2) and the force feedback from the slave (dotted line 3). In channel 1, the master velocity signals directly return in the form of the damping $b\dot{q}_m$, which can be treated as a simple damper. Channel 1 generates a certain amount of damping and this enhances the system stability by sacrificing transparency. Channel 3 feeds feedback signals from the remote slave side in order to provide useful information to the operator (Sun et al., 2014).

The phenomenon of wave reflection occurs in channel 2.

$$u_m(t) = -v_m(t) + \sqrt{2b}\,\dot{q}_m(t) \tag{5}$$

$$v_s(t) = -u_s(t) + \sqrt{\frac{2}{b}}F_e(t) \tag{6}$$

Based on (5) and (6), each incoming wave variable v_m and u_s is reflected and returned as the outgoing wave variable u_m and v_s. Wave reflections can last several cycles in the communication channels and then gradually disappear. This phenomenon can easily generate unpredictable interference and disturbances that significantly influence transparency (Niemeyer, 1996).

The velocity tracking and force feedback under the standard wave-based system shown in Fig. 2 can be defined as follows:

$$\dot{q}_s(t) = \dot{q}_m(t - T_1) - \frac{1}{b}\left[F_e(t) - F_h(t - T_1)\right] \tag{7}$$

$$F_h(t) = F_e(t - T_2) + b\left[\dot{q}_m(t) - \dot{q}_s(t - T_2)\right] \tag{8}$$

The wave reflections in channel 2 adversely influence the transmitted force and velocity signals so that $F_h(t)$ and $\dot{q}_s(t)$ are not equal to $F_e(t - T_2)$and $\dot{q}_m(t - T_1)$, respectively. Therefore, bias terms $-\frac{1}{b}[F_e(t) - F_h(t - T_1)]$ and $b[\dot{q}_m(t) - \dot{q}_s(t - T_2)]$, which are caused by the wave reflections inhibit the wave-based system from achieving position and force tracking, especially during the transient state of the system.

It should be noted that under the ideal condition when the teleoperation system is perfectly matched (Fig. 3), the feed-forward wave variable u_m and the feedback wave variable v_s only contain velocity and force information, respectively, which are shown as follows (Benedetti, Franchini, & Fiorini, 2001; Ching, 2006):

$$u_m(t) = \frac{b\dot{q}_m(t)}{\sqrt{2b}} \tag{9}$$