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Bilateral control of master–slave manipulators with constant time delay

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ABSTRACT

This paper presents a novel teleoperation controller for a nonlinear master–slave robotic system with constant time delay in communication channel. The proposed controller enables the teleoperation system to compensate human and environmental disturbances, while achieving master and slave position coordination in both free motion and contact situation. The current work basically extends the passivity based architecture upon the earlier work of Lee and Spong (2006) [14] to improve position tracking and consequently transparency in the face of disturbances and environmental contacts. The proposed controller employs a PID controller in each side to overcome some limitations of a PD controller and guarantee an improved performance. Moreover, by using Fourier transform and Parseval's identity in the frequency domain, we demonstrate that this new PID controller preserves the passivity of the system. Simulation and semi-experimental results show that the PID controller tracking performance is superior to that of the PD controller tracking performance in slave/environmental contacts.

1. Introduction

Over the past 3 decades, teleoperation technologies have been gradually growing through the world. Teleoperation is used in many applications such as space operation [1], handling of toxic and harmful materials [2], robotic surgery [3] and underwater exploration [4]. Teleoperation can be divided into two main categories, namely, unilateral and bilateral. In unilateral teleoperation, the contact force feedback is not transmitted to the master. In bilateral teleoperation, the remote environment provides some necessary information by many different forms, including audio, visual displays, or tactile through the feedback loop to the master side. However, the contact force feedback (haptic feedback) can provide a better sense of telepresence and as a consequence improve task performances [5].

There are many structures for the bilateral teleoperation system. Two main structures are two-channel (2CH) architecture [6] and four-channel (4CH) architecture [7,8]. In two-channel structure usually the master position is sent to the slave controller, and the contact force of the slave robot with the environment is directly transmitted to the master.

In bilateral teleoperation, there are two main objectives that ensure a close coupling between the human operator/master robot and slave robot. The first goal is that the slave robot tracks the position of the master robot and the other is that the force, that occurs when the slave contacts with the remote environment, accurately transferred to the master. When these conditions are met, the bilateral teleoperation system is called a transparent system. Lawrence [8] has shown that there is a tradeoff between the stability and transparency, the improvement of one will deteriorate the other. The delay existing in the network teleoperation system can destabilize the closed-loop system and degrade transparency.

Most previous studies on stability were based on the passivity formalism, such as scattering theory [9] and wave variables [10]. The key point for these approaches is to passify the non-passive communication medium with time delay. Although transparency of these two approaches is poor, the stability is robust against the communication delay and called the delay-dependent stability. A comprehensive survey on the delay compensation methods can be found in [11]. Chopra and Spong [12] proposed a new architecture which builds upon the scattering theory by using additional position control on both the master and slave sides. This new architecture has an improved position tracking and comparable force tracking abilities than the traditional teleoperator model of [9,10].

In [13], Lee and Spong, introduced a PD-based controller scheme for the teleoperation system that keeps position coordination

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and ensures the passivity of the closed-loop system. The main drawback of this structure is that the backward and forward communication delays must be exactly known and symmetric. Therefore, they removed these aforementioned restrictions in their recent works. They used the controller passivity concept, the Lyapunov–Krasovskii technique, and Parseval's identity, to passify the combination of the delayed communication and control blocks altogether since, the delays are finite constants and an upper bound for the round-trip delay is known [14,15].

Nuno et al. [16] showed that it is possible to control a bilateral teleoperation with a simple PD-like controller and achieve stable behaviour under specific condition on control parameters. According to the complexity of the communication network, the backward and forward delays are not only time-varying but also asymmetric. In [17,18], two different methods based on the PD controller have been presented to address these problems. The method in [18] uses a Lyapunov–Krasovskii functional to derive the delay-dependent stability criteria, which is given in the linear-matrix-inequality (LMI) form. Ryu et al. [19,20] proposed a passive bilateral control scheme for the teleoperation system with time-varying delay, which is composed of a Passivity Observer and a Passivity Controller. This controller guarantees the passivity of bilateral teleoperation under some condition, independent of the amount and variation of time-delay in communication channel. In [21], the authors also extended the previously proposed controller in [14]. The main difference is the use of stable neural network in each side to approximate the unknown nonlinear functions in the robot dynamics and enhance the master–slave tracking performance in the face of different initial conditions and environmental contacts. The new neural network controller preserved the passivity of the overall system.

In this paper, the passivity based architecture of [14] is extended to improve position tracking and consequently transparency in the face of environmental contacts. In this regard, a PID controller is employed in each side to overcome some limitations of PD controllers such as disturbance rejection. The key feature of the proposed PID controller is that it preserves the control passivity of the teleoperation system. For this purpose, we will use Fourier transform, Parseval's identity, and the Schur complement to show that the proposed PID controller with additional dissipation term will preserve the passivity of the system under some mild condition, since the time delays are constant. The majority of the passivity demonstration is done in the frequency domain.

The rest of this paper is organized as follows. Section 2 describes passive bilateral teleoperation structure with constant time delay introduced by Lee and Spong [14]. In Section 3, we describe the new control architecture based on the PID controller and demonstrate its passivity. Furthermore, we used a Nicosia observer [23] to estimate the human hand forces when the master does not have force sensor. Section 4 shows the simulation and experimental results. And finally Section 5 draws conclusions and gives some suggestions for future works.

2. Passive bilateral teleoperation structure with constant time delay

In [14], a novel control framework for bilateral teleoperation of a pair of multi-DOF nonlinear robotic systems with constant communication delays was proposed. The proposed bilateral teleoperation framework is shown in Fig. 1.

A bilateral teleoperation system which is shown in Fig. 1 consists of five interacting subsystems: the human operator, the master manipulator, the control and communication medium, the slave manipulator and the environment. The human operator commands via a master manipulator by applying a force $F_1(F_h)$ to move it with position q_1 and velocity $\dot{q}_1$ which is transmitted to the slave manipulator through the communication medium. A local control (T_2) on the slave side drives the slave position q_2 and velocity $\dot{q}_2$ towards the master position and velocity. If the slave contacts a remote environment and/or some external source, the remote force $F_2(-F_e)$ is sent back from the slave side and received at the master side as the force or control signal T_1.

Assuming the absence of friction, gravitational forces and other disturbances, the equation of motion for a master and slave nonlinear robotic system is given as follows [14]

$$M_1(q_1)\ddot{q}_1 + C_1(q_1,\dot{q}_1)\dot{q}_1 = T_1(t) + F_1(t) \tag{1}$$

$$M_2(q_2)\ddot{q}_2 + C_2(q_2,\dot{q}_2)\dot{q}_2 = T_2(t) + F_2(t) \tag{2}$$

where $q_i(t) \in \Re^n$ are the vector of joint displacements, $\dot{q}_i(t) \in \Re^n$ are the vector of joint velocities, $T_i(t) \in \Re^n$ are the control signals, $F_i(t) \in \Re^n$ represent the human/environmental force, $M_i(q_i) \in \Re^{n\times n}$ are symmetric and positive-definite inertia matrices and $C_i(q_i,\dot{q}_i) \in \Re^{n\times n}$ are the Coriolis/centripetal matrices ($i = 1, 2$). The Lagrangian robot dynamics enjoys certain fundamental properties [22].

- Property 1: The inertia matrix $M(q)$ is symmetric, positive definite and bounded so that

  $$\mu_1 I \le M(q) \le \mu_2 I$$

  where the bounds $\mu_i, i = 1, 2$ are positive constants.
- Property 2: The Coriolis/centripetal matrices can always be selected such that the matrix $\dot{M}(q) - 2C(q,\dot{q})$ is skew-symmetric.

The control objectives are designing the controllers $T_i(t), i = 1, 2$ to achieve these two goals:

I. *master–slave position coordination*: if $(F_1(t), F_2(t)) = 0$,

$$q_E(t) := q_1(t) - q_2(t) \to 0, \quad t \to \infty \tag{3}$$

II. *static force reflection*: with $(\ddot{q}_1(t), \ddot{q}_2(t), \dot{q}_1(t), \dot{q}_2(t)) \to 0$

$$F_1(t) \to -F_2(t) \quad \text{or} \quad F_h(t) \to F_e(t). \tag{4}$$

The closed-loop teleoperator (1)–(2) is said to satisfy the energetic passivity condition if there exists a finite constant $d \in \Re$ such that for $t \ge 0$:

$$\int_0^t \left[F_1^T(\theta)\dot{q}_1(\theta) + F_2^T(\theta)\dot{q}_2(\theta)\right] \mathrm{d}\theta \ge -d^2. \tag{5}$$

The teleoperator controllers hold the controller passivity if there exists a finite constant $c \in \Re$ such that for $t \ge 0$:

$$\int_0^t \left[T_1^T(\theta)\dot{q}_1(\theta) + T_2^T(\theta)\dot{q}_2(\theta)\right] \mathrm{d}\theta \le c^2. \tag{6}$$

This means that the energy generated by the master and slave controllers is always bounded [15]. It is shown that for teleoperation system (1)–(2), controller passivity (6) indicate energetic passivity (5). This allows us to investigate the passivity of the closed-loop teleoperator just by checking the controller structure and with no concern about the nonlinear dynamics of the master and slave robots [14].

The following PD-like controllers are proposed to guarantee the master–slave coordination (3), bilateral force reflection (4), and energetic passivity (5).

$$\begin{aligned} T_1(t) &= -K_\upsilon(\dot{q}_1(t) - \dot{q}_2(t-\tau_2)) - (K_d + P_\varepsilon)\dot{q}_1(t) \\ &\quad - K_p(q_1(t) - q_2(t-\tau_2)) \end{aligned} \tag{7}$$

$$\begin{aligned} T_2(t) &= -K_\upsilon(\dot{q}_2(t) - \dot{q}_1(t-\tau_1)) - (K_d + P_\varepsilon)\dot{q}_2(t) \\ &\quad - K_p(q_2(t) - q_1(t-\tau_1)) \end{aligned} \tag{8}$$

where $\tau_1, \tau_2 \ge 0$ are the finite constant communication delays, $K_\upsilon, K_p \in \Re^{n\times n}$ are the symmetric and positive-definite PD gains,