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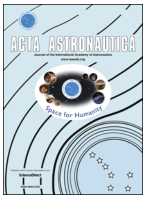

A self-adjusting compliant bilateral control scheme for time-delay teleoperation in constrained environment

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ABSTRACT

When teleoperations are implemented in the constrained environment, the lack of environment information would lead to contacts and undesired excessive contact forces, which are more evident with the existence of time delays. In this paper, a hybrid compliant bilateral controller is proposed to deal with this problem. The controller adopts a self-adjusting selecting scheme to divide the subspaces online. The master and slave manipulators are synchronized in the position subspace through an adaptive bilateral control scheme. At the same time, the slave manipulator is controlled by a local sliding mode impedance controller in order to achieve the desired compliant motion when contacting with the environment. Theoretical analysis proves the stability of the hybrid bilateral controller and concludes the transient performance of the teleoperators. Simulations are carried out to verify the effectiveness of the proposed approach. The results show that the control goals are all achieved.

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1. Introduction

In typical bilateral teleoperations, a human operator at the local site indirectly interacts with the remote environment via a pair of dual robotic mechanisms, usually called the master and slave robots. Meanwhile, the contact information is fed back from the remote side to the local site, providing the operator with a more extensive sense of telepresence, in which way the task performance can be consequently improved [1]. Bilateral teleoperations can be found in several fields such as on-orbit service, nuclear facilities maintenance, telesurgery, under water exploration, and so on [2–4].

The main challenge existing in bilateral operation is the time delay. The communication network between the master and slave robots usually suffers from substantial time delay, data limitation and information loss. The time delay existing in the loop would influence the stability and degrade the performance of teleoperation. Much effort has been devoted to overcome the time-delay instability, of which the best known methods are scattering theory and wave variable approach [5–7]. Both methods guarantee the stability of teleoperation systems by preserving the passivity of the communication channel. A series of subsequent researches were carried out based on those two methods. For more advanced surveys, the reader may refer to Hokayem & Spong [8], in which position feedback, impedance matching, time-domain passivity approach and various other objectives were introduced. Recently, the PD-based bilateral control was studied to synchronize the position of teleoperators and the corresponding stability criterions were proposed using Lyapunov–Krasovskii technique and Parseval's identity [9,10]. Adaptive

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bilateral control was also studied in the past few years, Chopra and Nuno proposed adaptive controllers for nonlinear teleoperators with time-delays respectively [11,12]. Both of their methods can realize the synchronization of teleoperators, but the estimates of parameters may be inaccurate because the persistent excitation condition (PE) [13] is difficult to meet during the teleoperation.

The majority of the existing studies merely focus on the position tracking or velocity tracking between the dual robots. However, this is not enough in most real-world applications. As is known to us, during the teleoperation, the telerobots often have to (voluntarily or involuntarily) contact the objects or environments in order to complete some complicated missions [14], such as target capturing or on-orbit maintenance in space activities, or touching the patient during the telesurgery. In this kind of tasks, in addition to synchronizing the teleoperators, the contact force should also be regulated. Therefore, the hybrid position/force bilateral control or the hybrid impedance bilateral control scheme is required and this becomes the motivation of our work. To the best of our knowledge, there are few works that have addressed the hybrid teleoperation problem so far. Li [15] proposed a hybrid position/force approach and proved the stability of the controller based on LMI conditions. The transient performance was not analyzed in his work.

In this paper, the problem of time-delay teleoperation in the constraint environment is considered. The telerobot is assumed to be subject to a unilateral constraint with unknown boundary. When contacts happen, the telemanipulator should behave compliant to the contact forces. To achieve this goal, an adaptive hybrid impedance bilateral control scheme is proposed. Under the framework, the position is synchronized by an adaptive bilateral controller, and at the same time, the contact force is locally controlled by a sliding mode impedance scheme. At the slave side, a self-adjusting mechanism is applied to update the subspaces for the hybrid control. The adaptive bilateral controller is proved to be robust to time delays and dynamic uncertainties. Different from the previous works, the proposed adaptive law is able to obtain accurate parameter estimates and therefore has guaranteed transient performance. The sliding surface is chosen according to the desired impedance characteristic so that the telemanipulator can behave compliant when contacting with hard environments.

The paper is organized as follows. The problem is formulated in Section 2. The design of the bilateral controller is presented in detail in Section 3. The stability and performance of the proposed is analyzed in Section 4. In Section 5, simulations are carried out to validate the proposed approach. The conclusion is drawn in Section 6.

2. Problem formulation

Consider the teleoperation system composed by a couple of n-DOF manipulators. In this work, only the non-redundant non-singular manipulators are considered, which means Jacobian J is smooth and nonsingular. Define the unilateral constraint as the following form,

Taking account of frictions, the dynamics of the teleoperators can be described in the task space by the following Euler–Lagrange equations[16]:

$$\begin{cases} H_m(x_m)\ddot{x}_m + C_m(x_m,\dot{x}_m)\dot{x}_m + D_m(x_m,\dot{x}_m)\dot{x}_m = u_m + F_h \\ H_s(x_s)\ddot{x}_s + C_s(x_s,\dot{x}_s)\dot{x}_s + D_s(x_s,\dot{x}_s)\dot{x}_s = u_s + G_\phi^T(x_s)\lambda \end{cases} \tag{1}$$

where the subscript $i(i=m,s)$ denotes the master and slave respectively. $x_i \in \mathbb{R}^n$ are the vectors of task variables (end-effector location), and $\dot{x}_i$, $\ddot{x}_i$ stand for the velocities and accelerations respectively. $H_i(x_i) \in \mathbb{R}^{n\times n}$ are the corresponding inertia matrices; $C_i(x_i,\dot{x}_i) \in \mathbb{R}^{n\times n}$are the Coriolis and centrifugal effects; $D_i(x_i,\dot{x}_i) \in \mathbb{R}^{n\times n}$ are positive-semidefinite diagonal matrices, denoting the joint friction coefficients. Since the gravity terms can be cancelled out by the feedforward control inputs, they are not considered in the dynamics for simplicity. $u_m, u_s \in \mathbb{R}^n$ are vectors of driving generalized forces. $F_h \in \mathrm{R}^n$ is the force of human operator imposed on the master manipulator. F_e is the contact force between the slave and environment. The following properties hold [17,18],

P1. The inertia matrices are symmetric positive definite, and uniformly positive definite with lower and upper bound,

$$0 < \lambda_{min}\{H_i(x_i)\}I \le H_i(x_i) \le \lambda_{max}\{H_i(x_i)\}I < \infty \tag{2}$$

P2. The Coriolis and centrifugal matrices $C_i(x_i,\dot{x}_i)$ satisfy that $\dot{H}_i(x_i) - 2C_i(x_i,\dot{x}_i)$ are skew-symmetric, i.e.

$$\dot{H}_i(q_i) = C_i(x_i,\dot{x}_i) + C_i^T(x_i,\dot{x}_i) \tag{3}$$

P3. The models are linearly parameterizable with a proper definition of the robot parameters, which means, dynamics (1) can be expressed as

$$H_i(x_i)\ddot{x}_i + C_i(x_i,\dot{x}_i)\dot{x}_i + D_i(x_i,\dot{x}_i)\dot{x}_i + g_i(x_i) = Y_i(x_i,\dot{x}_i,\ddot{x}_i)\theta_i \tag{4}$$

where $Y_i(x_i,\dot{x}_i,\ddot{x}_i) \in \mathbb{R}^{n\times p}$ are matrices of known functions, and $\theta_i \in \mathbb{R}^p$ are constant vectors of the manipulators.

If the master and slave manipulators are synchronized in task space, then teleopertors are coupled by

$$\begin{cases} x_s^d(t) = x_m(t-\Delta T), & \dot{x}_s^d(t) = \dot{x}_m(t-\Delta T) \\ x_m^d(t) = x_s(t-\Delta T), & \dot{x}_m^d(t) = \dot{x}_s(t-\Delta T) \end{cases} \tag{5}$$

where ΔT is the forward and back time delay of the teleoperator system.

When the slave manipulator moves in the constrained environment, it is not practical to require that the slave manipulator strictly follows the master in position, because the environment will probably hamper the motion in some directions. So the control goals are that the manipulators are synchronized in unconstrained subspace, while in the constrained subspace (where there are contact forces), the slave manipulator follows the master with a desired impedance characteristic.

3. Hybrid impedance bilateral control scheme

3.1. Framework of hybrid impedance teleoperation

Generally in teleoperation systems, the commands are all made by the human operator in master side, which

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