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A novel position and force coordination approach in four channel nonlinear teleoperation

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ABSTRACT

In this paper, a novel control scheme is presented to achieve simultaneous position and force coordination in nonlinear teleoperation systems. Providing force feedback would facilitate the task for the operator and increase the performance. The four channel architecture is employed for this target as a high transparent structure. However, the stability issue has been a challenging problem, even in the sense of linear teleoperators. By employing a novel nonlinear damping, the stability of the closed loop system has been preserved even when the communication channel is subjected to time varying delay. In addition, no passivity condition is required for both the operator and the environment, a restrictive condition which is not always held in practice. We also proved through Lyapunov–Krasovskii functions that position and force tracking error will asymptotically converge to zero. The controllers do not require any knowledge of the robot dynamics except the gravity terms. In order to verify the effectiveness of the proposed controller, a simulation result is presented, illustrating both position and force coordination in such nonlinear systems.

1. Introduction

Teleoperation has been put into practice since the mid 1940s, when there was a demand for remote manipulation of hazardous and inaccessible environments [1]. The operator can send commands through such systems, generating the desired motion by interacting with the master robot. This motion is transferred to the remote area via the communication channel and the slave robot has the duty to follow this motion. Some kinds of feedback from the remote environment can be provided for the operator, extending the amount of dexterity and knowledge of the environment. These characteristics has made teleoperation an appropriate approach, not only for space exploration [2] and excavation, but also for medical application such as telesurgery or teleoperated rehabilitation [3,4].

Teleoperation systems have a long history in the area of control theory. System modeling, stability and transparency are the three main challenges in teleoperation systems which researchers dealt over the past decades. For a long time, the only available modeling and analysis for the teleoperators was based on linear time-invariant (LTI) two-port networks [5,6]. This kind of modeling has its own advantages as there are more tools for stability analysis and performance measurements in the sense of linear control. For instance, some theorems such as Llewellyn's stability criteria or Nyquist theorem can be

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employed to show the absolute stability of these systems [7,8]. However, there are some deficiencies for this type of system presentation. First of all, the robot dynamics are nonlinear and highly coupled. As a result, it is preferred to use a general nonlinear multi-degree-of-freedom (DOF) robotic system for teleoperators. In addition, the communication network is subjected to time-varying delay which cannot be modeled by LTI elements. Moreover, it is restrictive to model the operator or the environment by LTI systems, since they possess nonlinear and time-varying dynamics [9]. As a result, a general nonlinear multi-degree-of-freedom (DOF) robotic system for teleoperators is preferred.

In order to conclude the stability of the teleoperation system, passivity has played a significant role as a conservative approach to achieve the closed loop stability [10]. The idea behind this approach is that feedback interconnection of any passive systems remains still passive and therefore stable [9]. Although the destabilizing effect of time delay was shown in teleoperation systems [5], many controllers were introduced to deal with this issue, passifying the network by adding extra damping. For instance, passivity observer and controller [11], scattering theory and wave variable [12] are examples of these approaches. However, the time delay is not the only element which can make the network non-passive. Operator and environment can also define non-passive mappings from torque to velocity in teleoperation systems [13]. The passivity based approaches cannot be employed when the two terminals are not necessarily passive. Furthermore, experiments show that passivity based controllers lead to 50% greater of task completion time. Also guaranteeing passivity has nothing to do with performance of the system [14,15].

The last point to analyze is system transparency while maintaining stability. Based on the type of information (motion/force) transmitted in the communication network, different architectures can be created. Among different architecture of teleoperation systems, four channel architecture is well-known for high transparency. This is mainly due to the existence of force feedback in both sides of terminals in addition to information of motion. Such force feedback provides a direct feeling for the operator about what is occurring in the environment [16,17]. Moreover, in accurate tasks such as telesurgery, absence of force feedback may increase the number of tissue damaging errors by a factor of 3 [18].

In the sense of linear teleoperation, it has been shown that under appropriate selection of controllers which cancels the dynamics of robot manipulators, the ideal transparent system can be theoretically achieved [19]. Meanwhile, this is not possible in practice and model-based controllers are not preferred since parameters of the manipulators are not exactly available. A full cancellation of system dynamics lead to a great tracking performance of force and position. Otherwise we should confine our objective to force and position coordination.

Many authors have considered some of the mentioned issues in their previous work. We intend to solely focus on the nonlinear modeling of teleoperation systems. For instance [9,12,20,21], lack one of the fundamental following assumptions or approaches: (I) Non-passivity of the operator or the environment (II) A non-conservative stability analysis behind the passivity concept (III) Transmitting the force information in network to provide a higher level of transparency (IV) Controllers with no knowledge of master/slave robot manipulators. The two most recent works [22,23] are more thorough. However, Li et al. assumed the time delay to be constant which is time-varying in practice [23]. In addition, there is no mathematical proof for position and force coordination of the system. Hashemzadeh et al. have considered the problem of nonlinear three channel teleoperation and all the mentioned issues have been addressed [22]. While if we extend our proposed controller to three channel case, one less force sensor is needed which decreases the cost and facilitates implementation. A complete comparison of this work and [22] is given later.

In this paper, a novel nonlinear control scheme will be presented to introduce a complete architecture for teleoperation systems. The dynamics of the master/slave robots are considered to be nonlinear and the communication network is subjected to time-varying delay. There is no restrictive condition on the passivity of the operator and the environment. As a main contribution of this work, force feedback is available for both terminals of the teleoperation system and also, stability and convergence of both position and force signals are proved. A novel nonlinear damper is introduced to stabilize the contact situation.

The rest of this paper is organized as follows. In Section 2 the model of teleoperation system is given. The proposed nonlinear control strategy and associated stability analysis are given in Section 3. Evaluating the performance of the controller and the behavior of the position coordination error are analyzed in Section 4. In Section 5 simulation results are given and finally conclusion and future works are discussed in Section 6.

2. Dynamic modeling

2.1. Robots properties

Consider the following master/slave multi-DOF manipulators :

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m = u_m + \tau_h \tag{1}$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s = u_s - \tau_e \tag{2}$$

where in (1), (2), $M_i(q_i)$, $C_i(q_i, \dot{q}_i)$ are $n \times n$ inertia, Centrifugal and Coriolis matrices, respectively. Assume gravity is locally compensated. Note that q_i , $\dot{q}_i$ and $\ddot{q}_i$ stand for joints position, velocity and acceleration, respectively. Subscript i means m: Master and s: Slave. Two properties for these manipulators are considered [24]: (I) The matrix $M_i(q_i)$ is symmetric positive definite (II) The matrix $\dot{M}_i(q_i) - 2C_i(q_i, \dot{q}_i)$ is skew symmetric.

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