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Research article

Passivity-based control framework for task-space bilateral teleoperation with parametric uncertainty over unreliable networks ☆

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A R T I C L E I N F O

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A B S T R A C T

Bilateral teleoperation systems developed in joint-space or in task-space without taking into account parameter uncertainties and unreliable communication have limited practical applications. In order to ensure stability, improve tracking performance, and enhance applicability, a novel task-space control framework for bilateral teleoperation with kinematic/dynamic uncertainties and time delays/packet losses is studied. In this paper, we have demonstrated that with the proposed control algorithms, the teleoperation system is stable and position tracking is guaranteed when the system is subjected to parametric uncertainties and communication delays. With the transformation of scattering variables, a packet modulation, called Passivity-Based Packet Modulation (PBPM), is proposed to cope with data losses, incurred in transmission of data over unreliable network. Moreover, numerical simulations and experiments are also presented to validate the efficiency of the developed control framework for task-space bilateral teleoperation.

1. Introduction

Bilateral teleoperation is a human-robot system that provides a platform to operators to physically interact with objects in remote or hazardous environments [1,2]. In this system, via a communication network, a slave robot can track the motion of a master robot, manipulated by a human operator, to carry out various kinds of missions remotely. Several control frameworks have been proposed by researchers in control and robotics communities to render stable teleoperation systems with guaranteed tracking performance [3–6]. As a fruitful research application, teleoperation has been extensively implemented in radioactive materials handling, outer space exploration, mobile vehicle operation, microparticles manipulation, and minimally invasive surgery [7–9]. However, most of the previous results were studied without taking into account two significant practical issues *simultaneously*:

(1) Robotic manipulators generally interact with human or objects on the end-effector without precise knowledge of physical parameters, and
(2) Packet-switching network usually incurs unavoidable communication unreliability, e.g. time delays and packet loss.

Therefore, a task-space bilateral teleoperation system has been developed in this paper under the consideration of parametric uncertainties and communication unreliability.

The presence of communication delays, which can destabilize and degrade system performance [10,11,6], is the most significant issue in the development of bilateral teleoperation systems. The stability of teleoperation systems subjected to time delays has been extensively studied by using scattering transformation [12–14], passivity-based technique [5,15], PD-like controller [16,2], and synchronization [3]. Although the aforementioned control algorithms can either stabilize teleoperation systems and/or guarantee position tracking, a joint-space control framework which does not deal with uncertainties makes such systems difficult to put into practice. Since robotic manipulators in teleoperation systems interact with human operators or workspace on the end-effector, e.g. cooperations with multiple manipulators [17], developing task-space teleoperators has become an emerging research area [18–23].

Most of the previous results in task-space teleoperation were developed under the assumption that the Jacobian matrices are exactly known with perfect measurement of kinematic parameters. As physical parameters of robotic systems are difficult to obtain precisely in practice, developing control algorithms by taking kinematic and dynamic uncertainties into account in robotic manipulators is necessary in the study of teleoperation [23,24,19]. A novel nonlinear adaptive controller was presented for

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teleoperation system subjected to both dynamic and kinematic uncertainties by using Lyapunov stability analysis [23]. However, the communication network was assumed to be perfect without time delays. A task-space teleoperation system was developed with system uncertainties and communication delays by using P+d and adaptive fuzzy P+d controller [24]. Recently, a systematic study of task-space teleoperator has been presented to deal with parametric uncertainties in robotic systems with constant delays and without velocity measurements [19].

In addition to parametric uncertainty, signals transmitted between the master and slave robots in a teleoperation are affected by the quality of service in the communication network. Due to long distance connection and bandwidth limitation, there are not only time delays in the transmission process, but packets might also get lost resulting from over-loading of the network devices. It has been demonstrated that time delays and packet losses are the two main issues that impede stability and transparency of teleoperation systems [25–27]. From the experimental results, the control framework using scattering transformation was reported to be more vulnerable to data losses compared to other methods. Therefore, several packet modulations have been developed to cope with the packet losses in teleoperation systems that are based on scattering transformation. A communication management module (CMM) was presented to ensure that the energy of input wave variables are greater than the output wave variables so that the passivity of the packet switched block is guaranteed [28]. However, tracking performance is not guaranteed, and the modulation is too complicated to implement in practice.

The study of control system in task-space bilateral teleoperators with parametric uncertainties and communication unreliability is in its infancy. Therefore, the objective of this paper is to develop a novel teleoperator control framework by taking into account dynamic/kinematic unknown parameters and time delays/packet losses simultaneously. In this paper, we first addressed a task-space teleoperation system without the knowledge of both dynamic and kinematic parameters. Stability, tracking performance, and force reflection are guaranteed in the proposed task-space nonlinear teleoperators with communication delays. Consequently, a novel modulation, called Passivity-Based Packet Modulation (PBPM), is addressed to cope with the proposed teleoperators when the communication network is subjected to time delays and packet losses. Furthermore, numerical examples and experiments are introduced so that stability and position tracking can be guaranteed for the proposed framework.

The results of this paper are summarized as follows.

- We develop a task-space bilateral teleoperation system taking into account both kinematic and dynamic uncertainties, whereas the conventional teleoperation systems mainly focus on joint space control.
- Unlike the previous results assumed either known Jacobian matrices, or perfect communication without packet loss, a passivity-based task-space teleoperation system is studied in this paper under parametric uncertainties and communication unreliability.
- We propose a novel packet modulation, which needs no knowledge of energy on the other side of the network block to deal with communication delays and data loss for teleoperation system using scattering transformation.
- Simulation comparisons and experimental results with force measurement are addressed in this paper to demonstrate better tracking performance and force reflection of the newly developed control algorithms than the other previously reported techniques.

This paper is organized as follows. Section 2 presents the theoretical results for task-space teleoperators with parametric uncertainties and communication delays. Stability, tracking performance, and force reflection of the proposed system with scattering transformation and packet-losses modulation are presented in Section 3. The verification results and comparisons with the previously developed schemes are shown in Section 4. Finally, conclusions and future research directions have been discussed in Section 5.

2. Passivity-based task-space teleoperation

Without loss of generality, the master and slave robots are modeled by Lagrangian systems (see Appendix) and driven by actuated revolute joints. Thus, the robot dynamics in the teleoperation system are given by

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

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

where the subscript m, s denote the signals of master and slave robots, $J_m, J_s \in R^{n\times n}$ are the Jacobian matrices, and $\tau_h, \tau_e \in R^n$ are the external human and environmental forces exerted on the end-effector of the master and slave robots, respectively. By following the robot kinematics for $i = \{m, s\}$, the relationships between the task-space and joint-space are given as $X_i = h_i(q_i)$ and $\dot{X}_i = J_i(q_i)\dot{q}_i$.

The control input for the task-space teleoperation system is given as

$$\begin{aligned}\tau_i &= \hat{M}_i(q_i)\dot{\chi}_i + \hat{C}_i(q_i, \dot{q}_i)\chi_i + g_i(q_i) + \hat{J}_i^T\bar{\tau}_i\\ &= Y(q_i, \dot{q}_i, \chi_i, \dot{\chi}_i)\hat{\theta}_i + g_i(q_i) + \hat{J}_i^T\bar{\tau}_i,\end{aligned} \tag{3}$$

where the second equality results from Property 1, $\hat{J}_i$ is the estimate of the Jacobian matrix, and $\bar{\tau}_i$ is the coupling control that will be defined subsequently. The control signals χ_i and $\dot{\chi}_i$ in (3) are designed by $\chi_i = -\lambda\hat{J}_i^{-1}X_i$, and $\dot{\chi}_i = -\lambda\dot{\hat{J}}_i^{-1}X_i - \lambda\hat{J}_i^{-1}\dot{X}_i$, where $\lambda \in R^+$ is a positive control gain, $\hat{J}_i^{-1} \in R^{n\times n}$ is the inverse of $\hat{J}_i$, and $\dot{\hat{J}}_i^{-1}$ is obtained by using $-\hat{J}_i^{-1}\dot{\hat{J}}_i\hat{J}_i^{-1}$ [29].

By defining $p_i = \dot{q}_i - \chi_i$, which leads to $\dot{p}_i = \ddot{q}_i - \dot{\chi}_i$, the closed-loop teleoperation system by using the control input (3) is given as

$$M_m(q_m)\dot{p}_m + C_m(q_m, \dot{q}_m)p_m = Y_m\tilde{\theta}_m + \hat{J}_m^T\bar{\tau}_m + \tau_h \tag{4}$$

$$M_s(q_s)\dot{p}_s + C_s(q_s, \dot{q}_s)p_s = Y_s\tilde{\theta}_s + \hat{J}_s^T\bar{\tau}_s - \tau_e \tag{5}$$

where $\tilde{\theta}_i = \hat{\theta}_i - \theta_i$ denotes the estimate error of unknown dynamic parameters.

In the absence of the knowledge of kinematic parameter vector ϑ_i for the robots, the actual Jacobian matrix is unknown to the controller. Therefore, the Jacobian matrices can only be obtained by utilizing the estimative values $\hat{\vartheta}_i$ in Property 5. For the robotic system with kinematic uncertainties, the estimated task-space velocity can be expressed as $\dot{\hat{X}}_i = \hat{J}_i(q_i)\dot{q}_i = Z_i(q_i, \dot{q}_i)\hat{\vartheta}_i$. Thus, the estimation error of the task-space velocity is $\dot{\hat{X}}_i - \dot{X}_i = Z_i(q_i, \dot{q}_i)\hat{\vartheta}_i - Z_i(q_i, \dot{q}_i)\vartheta_i = Z_i(q_i, \dot{q}_i)\tilde{\vartheta}_i$, where $\tilde{\vartheta}_i = \hat{\vartheta}_i - \vartheta_i$. Additionally, by defining $r_i := J_i p_i = \dot{X}_i + \lambda X_i$, we have

$$\hat{J}_i p_i = \hat{J}_i(\dot{q}_i - \chi_i) = \dot{\hat{X}}_i + \lambda X_i = r_i + Z_i(q_i, \dot{q}_i)\tilde{\vartheta}_i. \tag{6}$$

Under the aforementioned formulation, the estimated dynamic

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