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Bilateral teleoperation with delayed force feedback using time domain passivity controller

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ABSTRACT

Time delay is a long standing impediment of bilateral control and can destabilize the system evidently. This paper presents a mode-based approach to alleviate some of the problems associated with time delays in a master–slave robot system. The originality of the approach proposed mainly lies in its capacity to take into account explicitly the slave force feedback modified according to the output of *Passivity Observer* (*PO*). This method consists of a virtual slave environment model together with a *PO* to calculate the system energy on the master side. The local environment model is built by the parameters that are identified online at the slave side. Simulation results show the superior performance of the proposed control scheme in the presence of time delays. Experimental results, using a 1-DOF master–slave teleoperation system, support this conclusion.

1. Introduction

Recently, robots in master–slave configurations have been introduced in minimally invasive surgery. In order to accomplish safer and delicate surgical tasks using robotic manipulators, accurate and reliable reproduction of the haptic sensations to the surgeon are strongly required [1]. This requirement is generally characterized as the transparency of the master–slave system. Another main objective for teleoperation system design is stability. The system is required to be stable with respect to a set of uncertainties introduced by operator, communication channel, remote environment, and sensors. In practical applications, particularly where the master–slave system is performed over a long distance, the existence of communication delay creates some of the most challenging problems. In master–slave surgical robot system, it has confirmed that the surgeon effectively loses his/her ability to operate when the time delay exceeds 500 ms, even there is only visual feedback [2]. In presence of the haptic feedback, the surgeon's performance decreases significantly due to the time delay.

Time delay has long been known as a very challenging problem in the design of bilateral teleoperation controllers. In the literature, the design of robust controllers for delayed teleoperation systems has been paid significant attentions in the past two decades. The first systemized stabilization method of bilateral teleoperation systems was proposed by Anderson and Spong based on scattering theory [3]. They observed that the system instability is due to the non-passive nature of the communication channel. Later on, this strategy is studied further by Niemeyer and Slotine [4], who first proposed the notion of a wave variable. The wave variable algorithm is one of the most primitive methods to deal with the time delay problem by transmitting wave variables instead of power variables.

Although wave variable approach has been successfully used for the design of stable teleoperation systems, in practice, however, wave variable based teleoperation system performance can be degraded due to several reasons, among which are position drift between master and slave, significant oscillation and poor transient response. Various treatments for addressing these shortcomings have also been proposed, which require the use of Smith predictor [5], wave filter [6], position compensation [7], force compensation [8] at a cost to teleoperation system passivity or transparency. Recently, Li and Kawashima [9] presented an augmented wave variable controller based on impedance matching to address the wave reflection problem. The authors concluded that stable position and force tracking are achieved by the proposed teleoperation approach.

The above mentioned wave variable structure is solely designed from the point of view of system stability. To improve the actual system performance to users, many researchers have designed the delayed teleoperation system including performance criteria, e.g., position and force tracking. Leung et al. [10], Yan and Salcudean [11], and Shahdi and Sirouspour [12] proposed bilateral

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controllers for time-delay based on the H∞ optimal controller and the μ-synthesis frameworks. Lee and Spong [13] proposed a PD-based controller against time delay for improved position tracking performance. They enforced the teleoperated system passivity by passifying the combination of the communication channel and control blocks altogether rather than commonly used scattering based teleoperation. Sirouspour and Shahdi [14] proposed a model predictive control method to improve system transparency for delayed teleoperation systems. However, the above works do not evaluate their proposed controllers against transparency measures.

One alternative approach to compensate the time delay in the transmission channel is called model-based approach [15]. In this method, a remote environment model is created on the master side to duplicate the essential features of the remote slave robot and environment.

In [16], Mirtra and Niemeyer proposed a model mediated approach to bilateral teleoperation under large communication delays. An adaptive impedance control scheme to alleviate the problems of time delays is presented by Velanas and Tzafestas in [17]. A virtual environment method and the correction to deal with the time-delay were proposed by Li and Song in [18]. Recently, Winck [19] proposed a unified teleoperation framework that combines predictive robot and remote environment models with a model-mediated approach to space object haptic interaction. Experimental results show that a reliable haptic feedback to the operator can be achieved by the proposed algorithm using a laboratory testbed. However, a priori environment model used in this approach must be available.

In [20], Hannaford and Ryu proposed a Time Domain Passivity Control (TDPC) for guaranteeing the passivity of haptic interfaces. This approach does not require the power variables to be transformed into wave variables. Instead, a straight-forward notion of energy is used to define passivity of the system. Based on TDPC, Hou and Luecke [21] proposed a bilateral controller for teleoperation system with time delay, considering slave and environment as a big one-port network system. Ryu [22] proposed a passive bilateral control scheme for a teleoperator with time-varying time delay based on TDPC. However, the above works based on TDPC suffers from the sudden force change when the time domain passivity condition is breached.

To address the aforementioned shortcomings of the basic TDPC algorithm, in this paper, we propose a new algorithm that the passivity observer is calculated by the virtual local force from the environment model. This local force feedback is selected based on the value of the system passivity. Then, such a local force feedback is not subject to communication delay and then the stable position and force performances are achieved. Furthermore, a recursive environment parameter estimation method is utilized to resolve the potential problem introduced by virtual environment modeling errors. As a result, a stable teleoperation performance is achieved even there is time delay in the communication lines.

In more details, we present an approach to build a model of the remote environment on the master side together with a *Passivity Observer* (*PO*) of the system to observe the passivity of the teleoperation system. The control scheme of the teleoperation system is modified according to the output of the *PO*. The parameters of the environment are updated online based on delayed and possibly distorted measurement data. Then the idea was implemented to bilateral control, which is also known as position-force bilateral control architecture. After that, we analyze the performance of the proposed model based passivity controller taking into with/without the proposed method. At last, we experimentally evaluate and compare the performance of the performance of the proposed and a traditional wave variable based controller.

The rest of this paper is organized as follows: the time domain passivity control method and environment estimation techniques are introduced in Section 2. In Section 3, the general structure of the teleoperation system and the proposed bilateral control method are introduced. Section 4 discusses the modeling of remote environment and then online estimation techniques. Section 5 describes the simulations and experiments conducted to evaluate the performance of the system. Then, some discussion is given in Section 6. Finally, a summary and concluding remark are drawn in Section 7.

2. Time domain passivity and environment estimation techniques

2.1. Time domain passivity control

This section reviews the basic concepts of the TDPC approach. Loosely speaking, a system is said to be passive if the energy entering the system is greater than the outgoing energy. A system will be called passive if and only if

$$E(t) = \int_0^t P(\tau)d\tau + E(0) \geq 0 \tag{1}$$

where $E(t)$ is the total energy of the system at time t. $P(t)$ denotes the net power at input and output ports. $E(0)$ is the initial stored energy of the system at $t=0$.

In the case of teleoperation system, we are considering $f_{sd}(t)$, $\dot{x}_m(t)$ to be input—whereas $f_s(t)$,$\dot{x}_{md}(t)$ to be output-variable and assuming initial system energy $E(0)$ to be zero. The 2-port network can be characterized by the equation as follows:

$$E(t) = \int_0^t P(\tau)d\tau = \int_0^t (f_{sd}(\tau)\dot{x}_m(\tau) - f_s(\tau)\dot{x}_{md}(\tau))d\tau \geq 0 \tag{2}$$

which states that the energy supplied to a passive system must be non-negative for all time.

The passivity condition in Eq. (2) motivates the idea of time domain passivity control. The idea uses a *PO* to monitor $E(t)$ in real time. Depending on the operating conditions and the specifics of the element's dynamics, the *PO* may or may not be negative at a particular time. If it is negative at any time, the condition of being certain that the system may then be contributing to instability. Moreover, since the exact amount of the generated energy is known, the required amount of energy can be dissipated by a time varying damping element, called Passivity Controller (*PC*). Please see [18,21] for more details about the TDPC.

2.2. Environment estimation techniques

There exist several methods for online environment parameter estimation including Adaptive identification [23–25], Kalman filter approach [26,27] and Recursive least squares [28–30].

Singh and Popa [23] used a model reference adaptive control to estimate the environment parameters based on the environment model as linear spring in parallel with a viscous damper. They stated that environment parameter convergence can be guaranteed if the contact force is time varying. Hashtrudi-Zaad and Salcudean [24] employed composite adaptive control to achieve transparency for teleoperation in unknown environments. They estimated the parameters of the environment modeled by linear invariant mass-damper-spring systems. Seraji and Colbaugh [25] proposed the indirect adaptive controller to estimate the environment stiffness and location during each time step according to the update law. They concluded that a persistent excitation condition is needed for the convergence of the environment estimates to the correct value.

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