A passive bilateral control scheme for a teleoperator with time-varying communication delay

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ABSTRACT

In this paper, a passive bilateral control scheme is proposed for a teleoperator with time-varying communication delay. Recently proposed two-port time-domain passivity approach (TDPA), which composed of Passivity Observer (PO) and Passivity Controller (PC), is extended. A set of sufficient conditions is derived, which satisfies the passivity of the two-port delayed network system, by separating the input and output energy at each port. This condition satisfies the passivity of the network system independent of the amount of delay, its variation and lost packet. Two PCs are designed at each port based on its causality to guarantee the passivity condition. In order to filter out the sudden force change of the PC, a passive virtual dynamic system, composed of virtual mass and spring, is inserted between the master and the PC. Even under a large time-delay with variation and communication blackout, the proposed approach can guarantee passive bilateral teleoperation.

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1. Introduction

The field of teleoperation is getting considerable attention again [8] because of its potential applications, including tele-surgery and tele-maintenance and welfare. When a robot is operated remotely, force feedback can improve an operator's ability to perform complex tasks by kinesthetically coupling the operator to the environment. However, any data communication over the computer network has an intrinsic time-delay. In the presence of communication time-delay, even though it is small, force feedback has a strong destabilizing effect [28].

There have been numerous studies that have tried to solve the time-delay problem in the bilateral control of a teleoperator. Based on the scattering theory, Anderson and Spong [1] proposed a bilateral control law that maintains stability under the communication time-delay. Niemeyer and Slotine [17] extended this idea and introduced the notion of “wave variable”. Even though the wave variable method was successful, it assumed constant time-delay. Several approaches extended the original wave variable method to case where there was time-varying communication delay [6,7,12,16,18,31].

There were also several approaches based on the robust control theory. Leung [15] proposed a bilateral controller for time-delay based on the $H_\infty$ optimal controller and the $\mu$-synthesis frameworks. Oboe and Fiorini [9] and Lee [14] dealt with the time-delay problem over the Internet by using a simple PD-type controller. Santo [27] proposed a gain-scheduled $H_\infty$ controller by using measured time-delay. Haddadi and Hashtrudi-Zaad [9] introduced a design method for delay-robust transparent bilateral controller.

In [10], a new concept of the energy-based approach, also known as the time-domain passivity approach (TDPA), was proposed for guaranteeing the passivity of haptic interfaces. In TDPA, a “Passivity Observer” (PO) that could monitor energy in real-time and a “Passivity Controller” (PC) that could dissipate the required amount of energy based on PO were developed. Afterwards, TDPA was extended to teleoperation systems that had no communication time-delay [21]. Even though TDPA has been recognized as a simple and effective control method for haptic interfaces and tele-operation systems, there were some difficulties in extending this idea to include time-delay.

There have been several trials thus far that have extended TDPA to consider time-delay. In [11], the bilateral controller, slave and environment were considered as a big one-port network system, and the PO/PC was attached at the gate of a big one-port network. The whole one-port network could behave passively thanks to the PO/PC. However, it was found that the internal energy of the one-port network, like the states of the slave manipulator, cannot be regulated. Moreover, if the environment were active, this active energy would not be transmitted to the operator. Artigas et al. [3] approached the time-delay issue with two one-port networks. The bilateral controller, slave, and environment were considered to