Chapter 19

Four-Channel Control Architectures for Bilateral and Multilateral Teleoperation

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ABSTRACT

The four-channel architecture in teleoperation with force feedback has been studied in various existing literature. However, most of them focused on Lawrence architecture and did not research other cases. This paper proposes two other four-channel architectures: passive four-channel architecture and passive four-channel architecture with operator force. Furthermore, two types of multilateral shared control architecture based on passive four-channel architecture, which exists in space teleoperation, are put forward. One is dual-master multilateral shared control architecture, and the other is dual-slave multilateral shared control architecture. Simulations show that these four architectures can maintain stability in the presence of large time delay.

1. INTRODUCTION

Teleoperation has significant application in space (Sheridan, 1993; Nohmi, 2003), undersea (Jordán & Bustamante, 2007), toxic waste cleanup (Manocha, Pernalete, & Dubey, 2001), and telesurgery (Tavakoli, Patel, & Moallem, 2006; Tobergte, Konietschke, & Hirzinger, 2009) projects. A human operator conducts a remote task via the master and slave manipulators, and the contact force information is reflected to the human operator in bilateral teleoperation. The force-reflecting bilateral control can distinctly improve the performance in teleoperation, which enables the operator to feel present at the remote
location even though not really there. It is well known that the time delay is an intractable problem in bilateral teleoperation, especially in the space operations, the delay time sometimes will reach several seconds; this can easily destabilize the bilateral control system.

Up to now, the stability of a bilateral teleoperation system had been studied in various existing literature, and the most important method among them was passivity theory, which was introduced to the bilateral control to stabilize the system under random delay times. At first, Hannaford (1989) proposed a 2-port network mode, and took a hybrid matrix as bilateral representation, and then Anderson and Spong (1989) presented a control law for teleoperators by using passivity and scattering theory, which overcame the instability caused by time delay. Thereafter, Niemeyer and Slotine (1991) proposed a notion of wave variable to characterize time delay systems and got a new configuration for force-reflecting teleoperation. Kawashima et al. (2009) presented a controller for bilateral teleoperation based on the modified wave variable control method which provided superior position and force tracking performance compared to the traditional wave-variable-based method. Recently, Lee and Spong (2006) proposed a control framework for bilateral teleoperation of a pair of multi-degree-of-freedom nonlinear robotic systems under constant communication delays. Chopra et al. (2006) then improved the traditional passivity-based configuration by using additional position control on both the master and slave robots, to solve the steady-state position and force-tracking problem. Furthermore, Shahdi and Sirouspour (2009) proposed a systematic design procedure for improving teleoperation fidelity while maintaining its stability in the presence of dynamic uncertainty and a constant time delay.

With the development of the bilateral control strategy, Lawrence (1993) defined the performance of transparency and presented a general four-channel bilateral control mode. Since he proposed the four-channel control architecture, many researchers had amended and improved his works. For example, Hashtrudi-Zaad and Salcudean (2002) improved the Lawrence architecture and used master and slave local force feedback to improve the system performance and stability. Sumiyoshi and Ohnishi (2004) introduced the transformation of the Hashtrudi-Zaad architecture to clarify the meaning of the local force feedback. Guiatni et al. (2005) then utilized sliding-mode control in four-channel architecture. Naerum and Hannaford (2009) furthermore stated and proved necessary and sufficient conditions for transparency of the Lawrence architecture.

Although the Lawrence architecture has been studied by many researchers, it has many limitations which will be analyzed in detail in Section 2. In this paper, we propose a passive four-channel architecture, which maintains stability in the presence of arbitrary time delay. Furthermore, this mode is extended and passive four-channel architecture with operator force is put forward. In addition, Khademian and Hashtrudi-Zaad (2007) introduced four-channel multilateral shared control architecture for dual-user teleoperation system. By analyzing teleoperation tasks, we can find that not only dual-master mode is appeared, but also dual-slave mode is needed. Therefore, we introduce two types of multilateral shared control architecture based on passive four-channel architecture; one is dual-master multilateral shared control architecture, and the other is dual-slave multilateral shared control architecture. The simulations based on single degree-of-freedom (DOF) linear time-invariant (LTI) system will validate the performance of the bilateral and multilateral architectures. Finally, it is necessary to illuminate that part works in this paper has been reported in an international conference (Wang, Sun, Liu, & Li, 2010).

This paper is organized as follows: a description of passive four-channel architecture and passive four-channel architecture with operator force is