Control Engineering Practice 33 (2014) 35–47

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Controller designs for bilateral teleoperation with input saturation

Seung-Ju Lee, Hyo-Sung Ahn*

School of Mechatronics, Gwangju Institute of Science and Technology (GIST), 123 Cheomdangwagi-ro, Buk-gu, Gwangju 500-712, Republic of Korea

ARTICLE INFO

Article history:
Received 18 March 2013
Accepted 3 September 2014
Available online 7 October 2014

Keywords:
Bilateral teleoperation
Input saturation
Stability
Synchronization

ABSTRACT

Input saturation raises a stability issue in a bilateral teleoperation system when a master robot whose motion is induced by a human operator moves fast in abnormal situation and a slave robot cannot follow the motion command due to the input saturation. In this paper, we conduct rigorous stability analyses of the teleoperation system under the input saturation. We first extend analysis of teleoperation scheme proposed in Chopra and Spong (2004) to a case of the input saturation, in which analysis is valid for a local operation region whose size is dependent on the input capacity. We further develop a new control scheme that guarantees the stability for a global operation region. Therefore, the proposed control scheme can deal with extreme cases, e.g., the speed of motion of the master robot can be substantially greater than the actuator capability of the slave robot. Simulations and experiments are subsequently conducted to verify the effectiveness of the analyses.

1. Introduction

Teleoperation is a technology that enables a remote robot to act in the place of a human operator. A teleoperation system generally consists of a master robot, a slave robot, and a communication medium. A human manipulates the master robot, and information is transferred to the slave robot through the medium, and a slave robot then acts on an environment according to the information received. The applications of teleoperation include unmanned underwater vehicles, space robotics, and a robot for handling radioactive material (Hokayem & Spong, 2006).

Technically, there are many serious issues in bilateral teleoperation such as force feedback, stability, and synchronization.

Force feedback is critically important in teleoperation because this information is helpful in making a decision and results in more successful task. For example, in a remote robotic operation, a number of literatures reported that force information has reduced unintentional injuries and potential target damage (Okamura, 2009; Ortmaier et al., 2007; Wagner & Howe, 2007). Various methods measuring the environmental force have been developed in Hu, Castellanos, Tholey, and Desai (2002), Kennedy, Hu, and Desai (2002), and Lee and Ahn (2012). Related to this topic, the authors of Lawrence (1993) and Yokokohji and Yoshikawa (1994) raised 'transparency' issue which means how accurately the obtained force information is transferred to and realized in the master robot, and subsequently suggested the use of a '4-channel architecture' to improve the transparency. In Aziminejad, Tavakoli, Patel, and Moallem (2008a) and Yalcin and Ohnishi (2010), the implementation of the 4-channel architecture with communication delay was presented. Chopra, Spong, Ortega, and Barabanov (2006) also discussed transparency in a situation in which the velocities of these robots are zero; and there have also been practical approaches for dealing with this topic in Oboe (2001), Zemiti, Morel, Ortmaier, and Bonnet (2007), and Polushin, Liu, and Lung (2007).

Regarding stability issue, a key factor is time delay in communication line. According to Anderson and Spong (1989), the whole system becomes unstable if a time delay exists in the communication line, which is an unavoidable problem because a time delay always exists when communications occur over a long distance. However, if we carry out a scattering transformation on the communication signals, the communication system becomes passive independent of the amount of time delay, thereby increasing the system stability (Anderson & Spong, 1989). This theory is verified with experiment in Aziminejad, Tavakoli, Patel, and Moallem (2008b), and the scattering formalism is extended to bilateral teleoperators under time-varying delays and data loss by adopting communication management modules (CMM) (Chopra, Berestesky, & Spong, 2008). The time-delay also results in trade-off between transparency and stability. According to Lawrence (1993) and Hashtrudi-Zaad and Salcudean (2002), the above passivity-based approach improves stability against time-delay but shows relatively poor transparency; while, a hard contact force feedback in another control architecture which is suitable for high transparency causes oscillation of whole teleoperation loop under the time delay. For this reason, the architecture allows a small time delay for stability. In order to avoid the trade-off, sensor substitution techniques have been developed (Massimino & Sheridan, 1993; Prattichizzo, Pacchierotti, & Rosati,; Schoonmaker & Cao, 2006). In this technique, there is no direct force feedback loop to master

* Corresponding author.

http://dx.doi.org/10.1016/j.conengprac.2014.09.002
0967-0661/

robot; instead, there are another routes for transferring the force information to human operator such as audio, vision, and vibration display of measured force information.

Synchronization is a stronger property that not only the stability is basically satisfied but also positions of the master and slave robots are eventually matched. Due to packet losses over Internet communications and time-varying delays, a position offset between the master and slave robots occurs. In Ye and Liu (2010) and Fernandez Villaverde, Barreiro, Carrasco, and Banos (2011), additional control laws improving tracking performance based on the scattering transform method have been presented. According to Chopra and Spong (2004) and Chopra, Spong, and Lozano (2008), it has been shown that the synchronization can be theoretically guaranteed by making a 'kinematical lock' between the master and slave robots.

In this paper, we additionally consider the input saturation problem in the teleoperation. It has been pointed out that the input saturation may cause instability of the system or undesirable overshoot in the slave robot motion (Lee & Lee, 1991). Suppose that a human operator encounters an abnormal situation during his task and he makes the master robot move fast; then, the input of the slave robot should be rapidly increased in order to trace the master's motion. However, the input may reach a saturation point, and the slave robot cannot follow the abrupt motion. The situation could be worse in case that the human operator tries to apply the larger force because he cannot perceive that the input of the slave robot is saturated. Therefore, it is necessary to compensate or release the input saturation effects.

There have been some literatures trying to solve the input saturation problem. The basic idea of the solutions is 'slow input motion' in the master side. The authors of Ahn and Yoon (2002) applied anti-windup techniques which is a well-known technique to release the saturation effect; furthermore, the extra input that is difference between the calculated control input and the saturated input is reflected to the master side in order to give a restraint of the motion of human operator. Similarly, the authors of Lee and Lee (1991) used a nonlinear dynamic compensating loop, whose function is to increase the impedance of mater robot when input of the slave robot is saturated. In Kawai and Fujita (2008), a command governor modifies the reference trajectory of the slave robot in order to avoid the input saturation. The slow input motion can be implemented in hardware design such as intentionally designed high static friction. However, there have been no studies of stability analysis for the general robotic teleoperation system. The stability analysis is missing in Ahn and Yoon (2002), and that of Lee and Lee (1991) and Kawai and Fujita (2008) are based on the linear model. Because the master and slave robots are governed by the hardly nonlinear robotic dynamics, the analysis cannot guarantee the stability in whole workspace.

In this paper, we conduct the rigorous stability analyses of the teleoperation system under the input saturation. For the first analysis, we use the approach proposed in Chopra and Spong (2004) because the stability as well as synchronization are ensured under the nonlinear robotic dynamics. Based on the result, we extend the synchronization to the input saturation case. It will be shown that the synchronization is still preserved if the actuator capability is larger than a specific level that will be explained in this paper. For the second analysis, we develop another control scheme. The basic idea is that an additional feedback loop from the master side to the slave side is designed in order to consider the input saturation of master robot. This control scheme does not require any specific condition of the actuator capability; thus, the analysis is valid in a global operational region. Therefore, the advantage of the second scheme is that stability is still valid in a set of extreme cases, e.g., the speed of motion of the master robot can be substantial compared to the actuator capability of the slave robot. As the results, the control scheme guarantees a ultimate boundedness in the case of time delay in communication line and a synchronization in the case of no time delay.

It is necessary to mention that the results of this paper are a complete version of the two conference papers (Lee & Ahn, 2010, 2011). This journal version is mainly distinguished from the conference papers from the following four points. First, we have more rigorously analyzed the synchronization of the first control scheme. The full and complete proofs of the results are provided in this journal version. Second, system identification has been employed to conduct reliable simulation tests. Third, in this journal version, a number of experiments have been conducted in order to justify the theoretical results. Lastly, more comprehensive explanation of this research including and motivations, and full technical descriptions have been added in this journal version.

The remainder of this paper is organized as follows. In Section 2, a mathematical model of bilateral teleoperation and a definition of saturation are given. As main results, an analysis on robustness of the teleoperation scheme proposed in Chopra and Spong (2004) under input saturation is given in Section 3, and a new controller design and its analysis are presented in Section 4. In Section 5, we describe a experiment setup that is used for the experimental tests. There are simulation results in Section 6, and experimental results in Section 7. In Section 8, we conclude this paper.

2. Preliminaries

As a preliminary background, we provide a mathematical model of a teleoperation system and its basic properties, which will also be used in proof of the main result. Subsequently, a formal definition and properties of the input saturation are also presented.

2.1. Robot dynamics

A bilateral teleoperation system can be modeled as a form of robot dynamics. As such, the Euler–Lagrange equations for an n-link robot are as follows (Spong & Vidyasagar, 2008):

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

$$M_s(q_s)\ddot{q}_s + C_s(q_s,\dot{q}_s)\dot{q}_s + g_s(q_s) = \tau_s - F_e \tag{1b}$$

where $q_m, q_s \in \mathbb{R}^n$ are vectors of the joint displacements, $\dot{q}_m, \dot{q}_s \in \mathbb{R}^n$ and $\ddot{q}_m, \ddot{q}_s \in \mathbb{R}^n$ are vectors of the joint velocities and acceleration, respectively, $\tau_m, \tau_s \in \mathbb{R}^n$ are the control input torques, M_m, $M_s \in \mathbb{R}^{n\times n}$ are the inertia matrices, $C_m\dot{q}_m, C_s\dot{q}_s \in \mathbb{R}^n$ are the vectors of Coriolis and Centripetal torque, $g_m, g_s \in \mathbb{R}^n$ are vectors of the gravitational torque, and $F_h, F_e \in \mathbb{R}^n$ are the human factor torque and environmental torque, respectively. Note the subscript m indicates the master robot and s is the slave robot. In robot dynamics, there are some additional fundamental properties.

Property 1. *The inertia matrix $M(q)$ is symmetric positive definite and some positive constants m_1, m_2 exist such that*

$$m_1 I < M(q) < m_2 I$$

where I is an identity matrix.

Property 2. *$\dot{M}(q) - 2C(q,\dot{q})$ is a skew-symmetric matrix.*

Property 3. *The Lagrangian dynamics are linearly parameterizable such that*

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = Y(q,\dot{q},\ddot{q})\theta = \tau \tag{2}$$

where θ is a constant p-dimensional vector of inertia parameters (such as link masses, moments of inertia, etc.), and Y is an $n \times p$