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Absolute stability analysis of sampled-data scaled bilateral teleoperation systems ☆

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ABSTRACT

Stability of a bilateral teleoperation system may be jeopardized by controller discretization, which has been shown to involve energy leaks. This paper proposes a novel approach to analyzing the absolute stability of sampled-data bilateral teleoperation systems consisting of discrete-time controllers and continuous-time master, slave, operator, and environment. The proposed stability analysis permits scaling and delay in the master and the slave positions and forces. The absolute stability conditions reported here impose bounds on the gains of the discrete-time controller, the damping terms of the master and the slave, and the sampling time. A design-related application of these results is in proper selection of various control parameters and the sampling rate for stable teleoperation under discrete-time control. To explore the trade-off between the control gains and the sampling time, it is studied that how large sampling times, which require low control gains for maintaining stability, can lead to unacceptable teleoperation transparency and human task performance in a teleoperated switching task. This shows that the effect of sampling time must be taken into account because neglecting it (as in the absolute stability literature) undermines both stability and transparency of teleoperation. The resulting absolute stability condition has been verified via experiments with two Phantom Omni robots.

1. Introduction

A teleoperation system consists of a user interface ("master") that interacts with a human operator and a remote robot ("slave") that interacts with an environment. In bilateral teleoperation, while the slave robot mimics the motions of the master robot, the contact forces between the slave and the environment must be displayed to the operator by the master. Bilateral teleoperation has applications including telesurgery and remote underwater or space exploration. Surveys on bilateral teleoperation can be found in Hokayem and Spong (2006) and Arcara and Melchiorri (2002).

Teleoperation controllers are designed to meet two fundamental objectives, namely stability and transparency. Transparency is defined as matching of positions and forces of the master and the slave, and ensures that the environment's impedance is transmitted to the operator with no distortion. There is a trade-off between transparency and stability of a teleoperation system – the best performance is achieved by the least conservative stabilizing controller (Aziminejad, Tavakoli, Patel, & Moallem, 2008; Lawrence, 1993).

1.1. Teleoperation stability analysis

To analyze the closed-loop stability of a teleoperation system, one can assume that the operator and the environment models are known, e.g., in Tavakoli, Aziminejad, Patel, and Moallem (2008). While this assumption will simplify the stability analysis, it cannot be made in practice because the dynamic parameters of the human operator change in response to the specific requirements of the task at hand (Matsuoka & Howe, 2000), and the dynamic parameters of the environment are uncertain, time-varying, and nonlinear.

Modeling the teleoperation system as a two-port network (teleoperator comprising the master, the controller and communication channel, and the slave) coupled to two one-port networks (environment and operator) paved the way for ensuring closed-loop stability via teleoperator passivity, i.e., ensuring that the two-port network teleoperator is passive, which physically means the teleoperator is not generating any energy (Anderson & Spong, 1989; Nuno, Basanez, & Ortega, 2011). Indeed, ensuring the passivity of the teleoperator along with the assumed passivity of its two terminations will guarantee the passivity of the resulting interconnection and thus the closed-loop stability of the teleoperation system (Hannaford, 1989). The human operator impedance has been argued to be passive (Hogan, 1989). Passivity of the two-port teleoperator can be investigated via the scattering framework or Raisbeck's criterion (Haykin, 1970; Mendez & Tavakoli, 2010). In another passivity approach known as time domain

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passivity observer/passivity controller, the teleoperator's passivity is monitored in real time and in case of non-passivity the system is passified by adding damping to the system (Ryu, Kwon, & Hannaford, 2004).

Absolute stability analysis relaxes the passivity assumption on the teleoperator meaning that it allows the teleoperator to be non-passive as long as the closed-loop stability of the teleoperation system is preserved. Similar to passivity, the absolute stability approach assumes that the environment and the operator are passive but otherwise arbitrary. The absolute stability of a *continuous-time* two-port network can be assessed using Llewellyn's criterion (Abbott & Okamura, 2003; Cho & Park, 2005; Mahvash & Okamura, 2007). Recent studies have introduced geometric approaches inspired by criteria for unconditional stability of microwave systems to study the absolute stability of teleoperation systems (Haddadi & Hashtrudi-Zaad, 2009). The proposed method by Haddadi and Hashtrudi-zaad allows the environment and the operator to be non-passive with bounded impedance while the overall *continuous-time* teleoperation system is still stable.

Absolute stability breaks down the teleoperation system to three main blocks as shown in Fig. 1: a human operator (1-port network), an environment (1-port network), and a teleoperator (2-port network). The teleoperator absolute stability is concerned with the stability of the overall teleoperation system having assumed that the two 1-port terminations are passive but otherwise arbitrary. As shown in Fig. 2, the absolute stability of a 2-port network is also equivalent to the passivity of the 1-port network resulting from connecting the other port of the 2-port network to a passive termination (Haddadi & Hashtrudi-Zaad, 2009). The challenge that is fully addressed in this paper is how to ensure stability of the overall teleoperation system when the only information about the terminations (i.e., the human operator and the environment) is their passivity. The assumption of termination passivity has been integrated into the stability analysis using the mapping of the positive real region to a unit disc in the Nyquist plane by finding the proper linear fractional transformation. A simpler case of such mapping has been first introduced by Colgate and Schenkel (1997) for a 1-port system (i.e., the virtual wall) and in this paper has been extended to 2-port network by solving the combined dynamics of both the master and the slave robots in a teleoperation system.

As mentioned above, the assumption of passivity of the 1-port network terminations can be expressed by their positive realness for linear systems. A system with transfer function $Z(s)$ is positive real if and only if

(1) $Z(s)$ has no pole in the right half plane (RHP).
(2) Any poles of $Z(s)$ on the imaginary axis are simple with real and positive residues.
(3) $\mathrm{Re}\{Z(s)\} \geq 0$ for all $\omega > 0$.

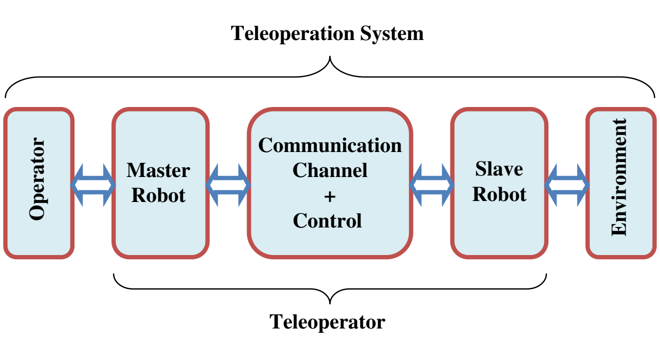

Fig. 1. The teleoperation system versus the teleoperator.

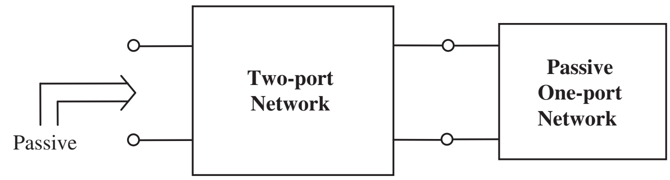

Fig. 2. Connecting a passive one-port network to any port of an absolutely stable two-port network results in a passive one-port network.

The effect of position and/or force scaling on the stability and passivity of a teleoperation system is a nontrivial problem. The conventional two-port network passivity analysis cannot be directly used in a scaled teleoperation system with arbitrary position and force scaling factors for the following reason. The two-port network representing the teleoperator is passive if the work done by the operator and the environment on it is non-negative at all times and for all inputs and initial conditions:

$$\int_0^t f_h(\tau)\dot{x}_m(\tau)\,d\tau + \int_0^t f_e(\tau)\dot{x}_s(\tau)\,d\tau > 0 \quad (1)$$

where f and $\dot{x}$ stand for force and velocity and subscripts h, m, e, and s correspond to hand, master, environment, and slave, respectively. The above energy balance equation has relied on defining the power at the input and output ports as the multiplication of a velocity and a force. If x_m and x_s are scaled with respect to each other, then it is obvious that f_h and f_e need to be at the inverse scale to make the input and the output powers comparable in the conventional passivity definition of (1) see (Cho & Park, 2002; Kosuge, Itoh, & Fukuda, 1996). In other words, the conventional passivity (1) cannot hold if both velocity and force at one termination of a teleoperation are at a smaller scale than those at the other termination which is against the transparency requirement (Boukhnifer & Ferreira, 2006). On the other hand, it will be elaborated that the proposed absolute stability approach is able to tackle the stability of a scaled teleoperation system with the same ease as when there is no power scaling.

1.2. Sampled-data teleoperation

A major challenge in stability analysis of teleoperation systems that is addressed in this paper is the effect of controller discretization. The discretization of a stabilizing continuous-time controller does not necessarily preserve the stability (Gillespie & Cutkosky, 1996; Leung & Francis, 1992). In fact, the stability of the closed-loop system will be degraded due to the energy-instilling behavior of the Zero Order Hold (ZOH) (Gillespie & Cutkosky, 1996). Moreover, once the continuous-time controllers of a continuous-time system are substituted by their discrete-time counterparts, the resulting sampled-data system will perform poorly especially if the sampling time is comparable to the fast dynamics of the controlled system. Fast dynamics exist, for example, when the environment of a teleoperated robot is stiff resulting in high-frequency contact forces. Thus, a sampled-data system analysis is required to consider the impact of discretization in a bilateral teleoperation system (Sheng & Liu, 2004). Consider haptic teleoperation on a finite-impedance object where slave–environment interaction forces are measured by a force sensor, sampled, and fed back to the user by a discrete-time controller. As the slave robot penetrates the environment, right at the edge of the environment, the environment does not resist and the force it applies to the slave robot is zero. As the slave robot's penetration into the environment increases, the resistive force coming from the environment increases. The measured contact force between the slave and the environment is sampled (during analog-to-digital conversion), and fed back to the human operator. Therefore, at any point in time during the