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Bilateral teleoperation system stability with non-passive and strictly passive operator or environment ☆

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ABSTRACT

A bilateral teleoperation system comprises a human operator, a teleoperator, and an environment. Without exact models for the teleoperator's terminations (i.e., human operator and the environment), it is typically assumed that they are passive but otherwise arbitrary. Based on this assumption, the stability of the teleoperation system is investigated through Llewellyn's absolute stability criterion for the teleoperator. However, the assumption of passivity of the terminations is less than accurate and may be violated in practice. Using Mobius transformations, this paper develops a new powerful stability analysis tool for a two-port network coupled to a passive termination and another termination that is (a) input strictly passive (ISP), (b) output strictly passive (OSP), (c) input non-passive (INP), or (b) disc-like non-passive (DNP). While this new stability criterion is applicable to any two-port network, we apply it to bilateral teleoperation systems with position-error-based (PEB) and direct-force-reflection (DFR) controllers. Simulations and experiments are reported for a pair of Phantom haptic robots.

1. Introduction

Stability analysis of a bilateral teleoperation system is challenging due to two typically unknown elements in its two ends: the human operator and the environment (Hannaford & Wood, 1989; Hokayem & Spong, 2006; Yan & Salcudean, 1996). For analysis of stability, a teleoperation system is typically modeled as a two-port network teleoperator connected to the two one-port network terminations (Fig. 1a), where the teleoperator comprises the master, the slave, their controllers, and the communication channel and the terminations are the human operator and the environment. By definition, absolute stability of a two-port network will guarantee the stability of the coupled system resulting from connecting the two-port network to two passive but otherwise arbitrary one-port network terminations. Equivalently, two-port network absolute stability requires that the driving-point impedance seen at one of the ports is passive when the other port is terminated to a passive one-port network (Fig. 1b) (Haykin, 1970). Therefore, the notion of absolute stability has been applied to the stability analysis of coupled two-port networks with limited information about the terminations.

1.1. Llewellyn's absolute stability criterion

For stability analysis of a bilateral teleoperation system, sometimes the passivity of the teleoperator is investigated (Anderson & Spong, 1989; Lee & Spong, 2006; Niemeyer & Slotine, 2004; Nuno, Basanez, & Ortega, 2011), which is sufficient for its absolute stability (Haykin, 1970). The teleoperator's absolute stability is a less conservative condition compared to its passivity. Due to stability-transparency trade-offs in a bilateral teleoperation system, minimizing conservatism in stability analysis is important (Kim, Chang, & Park, 2013; Lawrence, 1993; Li, Tavakoli, Mendez, & Huang, 2013).

A well-known absolute stability criterion for two-port networks was proposed by Llewellyn (1952) and applied to bilateral teleoperators (Adams & Hannaford, 1999; Aziminejad, Tavakoli, Patel, & Moallem, 2008; Hashtrudi-Zaad & Salcudean, 2001). Llewellyn's absolute stability criterion gives closed-form conditions involving the immittance (impedance, admittance, hybrid, and transmission, Aliaga, Rubio, & Sanchez, 2004) parameters of a two-port network for it to be absolutely stable (Haykin, 1970; Ku, 1963).

Abbreviation: LTI, linear time-invariant; PEB, position error based; DFR, direct force reflection; DFR(PD), force-position with PD position controller; DFR(P+D), force-position with P+D position controller; RHP, right half plane; LHP, left half plane; ISP, input strictly passive; OSP, output strictly passive; INP, input non-passive; ONP, output non-passive; DNP, disc-like non-passive; EOP, excess of passivity; SOP, shortage of passivity; OER, operator emulating robot

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Nomenclature

f_m	control signal for the master
f_s	control signal for the slave
f_h	operator's force
f_e	environment's force
x_m	master position
x_s	slave position
$C_m(s)$	position controller for master
$C_s(s)$	position controller for slave
k_{p_m}, k_{v_m}	proportional and derivative gains of C_m
k_{p_s}, k_{v_s}	proportional and derivative gains of C_s
Z_m	impedance of the master
Z_s	impedance of the slave
μ	position scaling factor
λ	force scaling factor
α	ratio $C_m(s)/C_s(s)$
β	initial energy of a passive system
δ	EOP of an ISP system
ϵ	EOP of an OSP system
η	SOP of an INP system
υ	SOP of an ONP system
ρ	SOP of a DNP system
Z_{ij}	the i-th row and j-th column element of an impedance matrix
R_{ij}	real part of Z_{ij}
I_{ij}	imaginary part of Z_{ij}
z_2	impedance coupled to port 2 of a two-port network
Z_{a1}	driving-point impedance at port 1 of a two-port network
A, B, C	parameters of a generalized circle in the complex plane

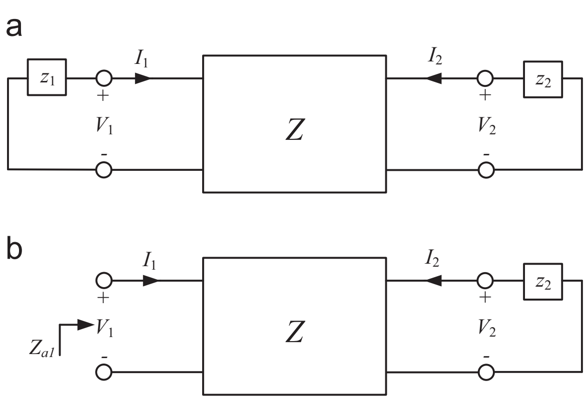

Fig. 1. (a) A two-port network connected to two one-port network terminations, and (b) the driving-point impedance at port 1, $Z_{a1} = V_1/I_1$, when port 2 is terminated to a passive impedance z_2.

1.2. Assumption on termination passivity

Llewellyn's absolute stability criterion requires both the terminations of the two-port network to be passive. Passivity of a linear time-invariant (LTI) system is equivalent to the positive-realness of its input–output relationship in the frequency domain (transfer function or impedance in the context of this paper) (Marquez, 2003). Equivalently, a passive LTI system has an impedance with its Nyquist diagram entirely in the right half of the complex plane (RHP).

Expecting the passivity of both the terminations of a teleoperation system can be unrealistic and overly restrictive in some applications. A two-port network's termination may simply be non-passive (Hirche, Matiakis, & Buss, 2009; Matiakis, Hirche, & Buss, 2009). On the other hand, a termination can be strictly passive. Later in the paper, we will discuss specific examples of such terminations for bilateral teleoperation systems. In this paper, a powerful tool is developed for stability analysis of a two-port network coupled to a passive termination and a non-passive or strictly passive termination with certain constraints on the termination's impedance.

Interestingly, to have a stable coupled system, it suffices if, after terminating the two-port network to a one-port network that is not necessarily passive, the driving-point impedance seen at the remaining (i.e., open) port is passive. This is because connecting a passive termination at the currently open port of this two-port network will inevitably result in a passive and thus stable system even though the opposite port might have been connected to a non-passive termination. As we will see later, this can be explained by the concepts of excess of passivity (EOP) and shortage of passivity (SOP) for feedback-interconnected systems. Briefly, when two systems are connected in a negative feedback loop, the stability of the interconnected system is guaranteed if both systems are passive. If one of the system has EOP, the other system may have SOP without risking the instability of the interconnected system (Sepulchre, Jankovic, & Kokotovic, 2012).

1.3. Leveraging termination knowledge in stability analysis

Utilizing knowledge about a termination in the analysis of stability of a coupled two-port network has been increasingly investigated by researchers. For instance, knowing a lower or upper bound on the impedance of a termination helps to model the termination as an arbitrary impedance coupled to a series or shunt impedance, respectively (Adams & Hannaford, 2002; Hashtrudi-Zaad & Salcudean, 2001). In another work, notion of bounded impedance absolute stability (BIAS) is applied to a teleoperation system in the scattering domain and the resulted stability conditions are expressed as bounds on the reflection coefficients (Haddadi & Hashtrudi-Zaad, 2012). The teleoperation system can be modeled in the integral quadratic constraints (IQC) formulation to reestablish stability conditions with known bounds on the termination (Polat & Scherer, 2012).

Also, recent work shows that conventional absolute stability criteria can be extended to strictly passive (Jazayeri & Tavakoli, 2012b) and non-passive terminations (Jazayeri, Dyck, & Tavakoli, 2013).

In recent works, stability analysis of two-port network systems has been studied when the terminations are either ISP or INP. In Jazayeri and Tavakoli (2012b) two approaches are applied to extend Llewellyn's absolute stability. In the first approach, the driving point impedance at port 1 is assumed to be in the RHP and the admissible Nyquist region for termination 2 is found. In the second approach, port 2 is assumed to be a right- or left-shifted RHP and the resulting driving-point impedance at port 1 becomes a disc, which should be entirely in the RHP for stability of the coupled two-port network. In Jazayeri et al. (2013), the second approach is applied when the terminations are non-passive rectangular impedance or right-shifted RHP impedances. In both the above work, the stability analysis is applied to a PEB-controlled bilateral teleoperation systems. This paper leverages the second approach when the terminations are INP/ISP/ONP/DSP/OSP and applies the results to PEB- and DFR-controlled bilateral teleoperation systems. In addition, this paper verifies the resulting stability