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# Quantitative analysis and evaluation of bilateral control schemes applied to electro-hydrostatic actuators☆,☆☆

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ABSTRACT

A bilateral teleoperator allows operators to use a master manipulator to interact with the environment via a slave manipulator. It can be used in remote, hazardous or inaccessible situations. Although numerous bilateral teleoperation studies have been conducted on electrical actuators, research on hydraulic actuators, especially research on electro-hydrostatic actuators (EHAs), a class of pump-controlled systems, is currently limited. In bilateral teleoperation, one issue concerns how to tune the controller parameters with regard to stability and transparency in the presence of uncertainty. In this paper, an approach based on quantitative feedback theory (QFT) that provides guidance on controller parameter selection during the bilateral teleoperation of EHAs is introduced. Parametric uncertainties in dynamics of human operators, master manipulators and environments are described in templates to compute bounds quantitatively, and trade-offs between stability and transparency are visualized. Four commonly used bilateral control schemes are exemplified using this method: force reflection (FR), position error (PE), shared compliant control (SCC) and force reflection with passivity (FRP). The bilateral controllers are tuned through simulations and are validated through contact experiments involving both soft and hard environments. Given its simple structure and excellent level of transparency, FR is found to be the most suitable scheme of the four for teleoperations of EHAs.



## 1. Introduction

A teleoperator is a pair of robot manipulators connected by a communication link that allows an operator to use a master to interact with a remote environment via a slave [1]. It is particularly useful for operations in remote, hazardous or inaccessible situations. Telepresence [2] is achieved when kinesthetic information on the remote side is fed back to the operator to reproduce an environment and to then guide a manipulation. The process is enabled by haptic devices such as PHANTOM Omni. The two-port network structure [3] has been extensively used in system analyses, in which efforts (force) and flows (velocity) at both terminals are bidirectionally exchanged through bilateral control. Bilateral teleoperators are currently used in a wide range of applications (e.g., underwater and outer-space exploration, radioactive fuel management, construction machinery and tele-surgery) [4].

System stability and transparency are two major issues of bilateral control. In addition to stability, a fundamental requirement of any control system, transparency between the impedance the operator perceives and that of the actual environment is required [5]. Communication delays can also become an issue when time delays in the communication link are noticeable (e.g., in the case of subsea or outer-space exploration). In addition, it is still challenging to tune controller parameters in the presence of uncertain dynamics of human operators, master manipulators and environments [6]. More specifically, when closing the loop with perceptions of remote kinesthetic information and when sending commands to the master manipulator, the human operator in the loop is tightly coupled with the teleoperator's performance. While previous studies have been conducted on this issue [7,8], there are currently no widely used models or exact parameters on human arms of teleoperation systems. Indeed, a human arm is an active system that behaves differently in different situations. In addition, the exact mathematical models and parameters of haptic devices are difficult to obtain [9].

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Numerous bilateral teleoperation studies have been conducted based on electrical actuators. In the late 1980s, network theory was employed to describe a teleoperation system and to analyze its stability. Raju et al. [2] used a two-port impedance network structure while Hannaford [1] utilized a two-port hybrid representation to describe a single degree of freedom teleoperation system. Anderson and Spong [3] applied scattering theory and passivity-based control to a teleoperator in the presence of time delays. Niemeyer and Slotine [10] applied the principle of wave variables and wave transmission to characterize a time-delayed system and formed a new configuration for force reflection teleoperations. Lawrence [5] explored telepresence performance using the notion of transparency and employed a general four-channel bilateral architecture. Considering the dynamics of both operators and environments, Yokokohji and Yoshikawa [11] defined three ideal responses and created a quantitative index for evaluating maneuverability. Several common bilateral control schemes were also experimentally evaluated through electrical actuation systems [12].

For heavy-duty applications such as construction or mining machinery, hydraulic actuators are preferred to their electrical counterparts. Although many bilateral teleoperation studies have been conducted on electrical actuators, research on hydraulic actuators is currently limited. Salcudean et al. [13] applied a dual hybrid teleoperation scheme to a hydraulic mini-excavator to achieve bilateral matched impedance control. Ahn [6] employed a force reflecting joystick for a bilateral teleoperated hydraulic excavator. He proposed a force reflection gain-selecting algorithm based on artificial neural network. Li and Krishnaswamy [14] proposed a passive control scheme for the bilateral teleoperation of a hydraulic actuator. Zarei-nia et al. [15] experimentally evaluated various bilateral control schemes using a valve-controlled hydraulic actuator. They further proposed a Lyapunov's feedback controller for haptic-enabled teleoperation systems [16].

Note that all of the abovementioned studies are based on valve-controlled hydraulic systems. To the best of the authors' knowledge, this is the first published work on the bilateral teleoperation of electro-hydrostatic actuators (EHAs). EHAs were introduced in the late 1990s based on the principle of closed-circuit hydrostatic transmission [17], which allows for variable power transmission by connecting a pump directly to an actuator. The flow rate into the system is volumetrically controlled by regulating either the speed or the displacement of the pump/actuator. Compared to traditional valve-controlled actuators, EHAs effectively remove throttling losses and prevent the formation of bulky centralized oil supplies. They combine the benefits of both conventional hydraulic and electrical actuators (i.e., high power-to-weight ratios and modularity). Over the past two decades, EHAs have been successfully applied to undersea vehicles and aircrafts [18]. Book [19] presented the prospect of energy-efficient hydraulic actuated mobile equipment with haptic interactions. His group further developed two excavator interfaces enabled by a haptic device and a kinematically similar joystick, respectively, and evaluated their usability over traditional excavators [20,21]. Given the above listed benefits and the practicability as in Book's research, bilateral control applied to EHAs is still a novel and promising approach. Previous studies on electrical actuators cannot be applied to EHAs because in electrical actuators, control signals (input currents) simply control the torque or force, whereas in EHAs, signals control the derivative of pressure, which is then translated into force. This renders the analysis of EHA control systems much more involved and challenging.

This paper introduces, for the first time, a practical quantitative analysis approach for studying different bilateral control schemes applied to an EHA-based teleoperator experiencing uncertainty. The proposed approach is enabled through quantitative feedback theory (QFT) [22]. Uncertainties in dynamics of human operators, haptic devices and environments are described in templates that compute bounds quantitatively, and the trade-off between stability and transparency is visualized. Four commonly used bilateral control schemes are used to carry out the evaluation: force reflection (FR) scheme [3], position error (PE) scheme [23], shared compliant control (SCC) scheme [24] and force reflection with passivity (FRP) scheme [10]. These four schemes represent a broad range of techniques, and they have been proven applicable to valve-controlled hydraulic actuators [15]. Performance criteria are defined as position tracking, force tracking and transparency between the perceived and actual stiffness. The four bilateral schemes are experimentally applied to a typical EHA for both soft and hard contact tasks. The results shown within the criteria are analyzed, and the main characteristics of each scheme are evaluated. Our validation of these schemes reveals the potential for developing bilateral teleoperated energy efficient hydraulic actuators.

The remainder of this paper is organized as follows. The modeling of an EHA-based teleoperator is described in Section 2. Following a brief introduction to QFT, an FR scheme is used in Section 3 to exemplify the controller parameter selection process enabled by QFT followed by three other bilateral control schemes. Based on the controller parameters obtained from Section 3, our experimental results and analysis are presented in Section 4. Conclusions are given in Section 5.

## 2. Modeling EHA-based teleoperator

The general information flow of a teleoperation system with negligible communication delays is represented in Fig. 1. It is composed of a human operator, a master, a communication block, a slave and an environment. Force and displacement information are bidirectionally exchanged.

To design bilateral controllers for the EHA-based teleoperator and to ensure good performance in the presence of uncertainty, an appropriate modeling of each element is of central importance.

The human arm, with muscles working as engines, is an active dynamic system that can perform differently in different situations. To depict it reasonably in a passive way, it is simplified as a spring with inevitable stiffness variation due to the adaptive instincts of the human body. Referring to [16], the combined dynamics of a human arm and haptic device in one dimension are written as

$$F_\mathrm{h} - F_\mathrm{m} = m_\mathrm{m}\ddot{x}_\mathrm{m} + c_\mathrm{m}\dot{x}_\mathrm{m} + k_\mathrm{h}x_\mathrm{m}, \tag{1}$$

Thus, the transfer function on the master side from force to displacement can be represented as

$$H(s) = \frac{x_\mathrm{m}}{F_\mathrm{h} - F_\mathrm{m}} = \frac{1}{m_\mathrm{m}s^2 + c_\mathrm{m}s + k_\mathrm{h}}, \tag{2}$$

where $F_\mathrm{h}$ is the force generated by the human operator's hand, $F_\mathrm{m}$ is the force generated by the haptic device based on certain control laws, $x_\mathrm{m}$ is the master displacement value, $m_\mathrm{m}$ is the combined mass of the haptic device and human arm, $c_\mathrm{m}$ is the combined viscous coefficient, and $k_\mathrm{h}$ is the stiffness of the human arm. A reasonable range for parameters in $H(s)$ [16,25] is given by $m_\mathrm{m}\in[0.05, 0.15]$ kg, $c_\mathrm{m}\in[1, 5]$ Ns/m, $k_\mathrm{h}\in[10, 25]$ N/m.

According to Massie and Salisbury [26], to achieve controllable and precise manipulation, a human rarely exerts a force of more than 10 N. In fact, the time averaged force exerted during normal operation is usually on the order of 1 N. On the other hand, the maximum applicable force of a haptic device is 3.3 N [25] while its continuous force capability is roughly 1.5 N [26]. Thus, in the simulation studies, $F_\mathrm{h}$ is set as a constant, 1 N, for the evaluation of all schemes, and the force perceived by the human arm, $F_\mathrm{m}$, should be less than 1 N.

With respect to the slave manipulator, an EHA is composed of a servo motor, a fixed displacement pump, a double-rod cylinder and