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Digital versus analog control of bilateral teleoperation systems: A task performance comparison

Ting Yang [a,b,*], Yili Fu [a], Mahdi Tavakoli [b,*]

[a] State Key Laboratory of Robotics and Systems, Harbin Institute of Technology, Harbin, 150080, China
[b] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta , Canada T6G 2V4

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ABSTRACT

Controller discretization has the potential to jeopardize the stability of a bilateral teleoperation system. As reported in the literature, stability conditions impose bounds on the gains of the discrete-time controller and the sampling period and also a trade-off between the two. This paper shows a choice of task for which large sampling periods, necessitating low control gains for maintaining stability, lead to low teleoperation transparency and unacceptable task performance. It continues to show that users can successfully perform the same task if the controller is implemented using analog components. This highlights the advantages of analog haptics in tasks involving the display of highly stiff environments. The paper also highlights the constraints in designing analog haptic teleoperation controllers and proposes design guidelines to address them.

1. Introduction

Digital techniques have liberated control designers from time-consuming analog design. However, this means the advantages of analog control have been abandoned (Ashrafzadeh, 2007; Hewitson, 2010; Brezovich, 2011; Malcher & Falkowski, 2014), which may cause significant performance and stability consequences. This paper studies whether an analog controller can achieve better user task performance compared to a digital controller in bilateral teleoperation.

A bilateral teleoperation system consists of three parts shown in Fig. 1: A human operator performing a task on an environment through a teleoperator. The teleoperator itself has three parts: A master user interface for the human operator, a slave robot acting at the environment, and a controller to ensure stability and performance (transparency). The relatively independent work spaces of the master and the slave let bilateral teleoperation be used in harsh, unsafe, remote or confined areas not appropriate for human presence, such as is the case in underwater or space exploration and telesurgery (Sheridan, 1989).

Controllers in teleoperation systems must satisfy two important indicators, that is, stability and transparency. When we discuss the stability, sometimes passivity of the teleoperator is studied instead (Colgate & Schenkel, 1997; Diolaiti, Niemeyer, Barbagli & Salisbury, 2006; Lee & Spong, 2006; Nuno, Basanez & Ortega, 2011; Li, Tavakoli, Mendez, & Huang, 2013). Or, the less conservative approach of absolute stability can be utilized (Adams & Hannaford, 1999; Aliaga, Rubio & Sanchez, 2004; Aziminejad, Tavakoli, Patel, & Moallem, 2008; Jazayeri & Tavakoli, 2012; Jazayeri & Tavakoli, 2013). Regardless, both approaches indicate that for a stable sampled-data teleoperation system, there needs to be an upper bound on the product of the control gain and the sampling period.

While the stability is a requisite for operation of the system, transparency is the ability of the system to transmit forces and positions from one end to the other end of the system without distortion. It is important to make sure the controller in a teleoperation system is designed such that high transparency is achieved. This will ensure that the human operator can perform a task through a teleoperation system with the same ease and performance that he/she does it in a direct-touch situation. In other words, transparency (system performance) and user task performance go hand in hand.

As will be discussed in Section 3, a larger control gain generally *leads* to higher system transparency, and therefore, improves user task performance. However, when the teleoperation controller is implemented in discrete-time (D-T), the product of control gain and sampling period is upper bounded as a condition for keeping the system stable. In practice, the value of the sampling period is lower bounded because of the time required for A/D and D/A conversion and the control law implementation, thus resulting in an upper bound on the control gain as far as stability is concerned. A major difficulty arises if this stability-imposed upper bound on the control gain constrains the teleoperation transparency to the level that tasks cannot be completed successfully by the human operator.

One way of solving the aforementioned dilemma is to use fast-sampling processors that provide very small sampling periods

* Corresponding author.
E-mail addresses: tyang1@ualberta.ca (T. Yang), ylfms@hit.edu.cn (Y. Fu), tavakoli@ece.ualberta.ca (M. Tavakoli).

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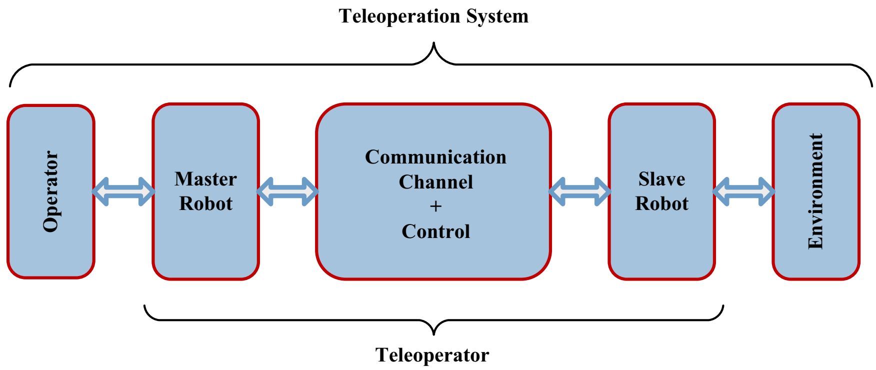

Fig. 1. A teleoperation system block diagram.

(Nealen, Muller, Keiser, Boxerman, & Carlson, 2006; Courtecuisse et al., 2010; Mafi et al., 2010; Spinner, Srinivasan, & Rengaswamy, 2014), but this option will be more expensive than the ubiquitous personal computers. Recently, a method is proposed by Susa and Takehana (Susa & Takehana, 2014), which divides the force presented to the human operator into two parts: a penalty force to render shapes and a vibration force. The penalty forces are unique for different materials, which can be detected from preliminary experiments.

A more affordable way is to use analog components to implement the teleoperation controller. As the analog system does not sample data, it is expected to fundamentally eliminate the limitation brought by the sampling period. This article discusses whether a bilateral teleoperation system with a continuous-time (C-T) analog controller can accomplish tasks requiring high positioning precision (high transparency), which require high-gain control, while maintaining the system stability.

`The paper is organized as follows. The bilateral teleoperation system used in this paper is modeled in Section 2. A detailed discussion of stability and transparency conditions needed in our teleoperation system is presented in Section 3. The experimental teleoperation system and the design differences between continuous-time and discrete-time controllers are shown in Section 4. Section 5 presents constraints brought upon by the two classes of controllers. Section 6 provides the control design procedure considering the constraints mentioned above. An empirical approach for designing the continuous-time teleoperation controller is presented in Section 7. Then, the experimental results concerning the teleoperation system performance are shown in Section 8. Further, the parameters of hybrid matrix H of discrete-time controlled and continuous-time controlled teleoperation systems have been found and compared in Section 9. In Section 10, the human performance of a switch-flipping task under continuous-time controlled and discrete-time controlled teleoperation systems is studied and compared. Lastly, concluding remarks are given in Section 11.

The contribution of this paper is in showing that a continuous-time controller can significantly increase the teleoperation system transparency when compared to its discrete-time counterpart (i.e., the discretized version of the same controller). This improvement in teleoperation system transparency is shown via a user study to translate to enhanced user task performance for the particular task considered in the paper. In this way, the paper shows that the root cause of task failure in teleoperation can actually be control sampling (while the blame is routinely placed on ubiquitous non-idealities such as friction, noise, control signal saturation, un-modeled dynamics, communication channel delay, etc. but not on sampling). The continuous-time controller provides these benefits without endangering the system stability. Another contribution of the paper is in providing a systematic design approach for the continuous-time haptic teleoperation controller.

2. System modeling

In this section, the bilateral teleoperation system used in the subsequent sections is modeled, including the forms of teleoperator, continuous-time dynamics of input–output and discrete-time input–output relations.

2.1. System modeling

The block diagram of a position-error-based (PEB) bilateral teleoperation system is shown in Fig. 2. Here, F_h is the interaction force between the master robot and the human operator, and F_e is the interaction force between the slave robot and the environment. Also, $\tilde{F}_h$ and $\tilde{F}_e$ represent the exogenous human operator and environment forces, respectively. X_m and $X_s$denote the position of the master and slave robots, respectively. Z_h and Z_e are the operator and environment impedances, respectively. The continuous-time models of the human operator and the environment are:

$$\begin{aligned}\tilde{F}_h - F_h &= Z_h(s)sX_m \\ \tilde{F}_e - F_e &= Z_e(s)sX_s\end{aligned} \tag{2.1}$$

where s is the Laplace operator.

The continuous-time dynamics of the master and slave robots in the s-domain are:

$$\begin{aligned}sX_m &= Z_m(-F_m + F_h) \\ sX_s &= Z_s(-F_s + F_e)\end{aligned} \tag{2.2}$$

where F_m and F_s are the control signals for the master and the slave, respectively. Z_m, $Z_s$represent impedances of the master and slave robots and are considered to be:

$$\begin{aligned}Z_m &= \frac{1}{m_m s + b_m} \\ Z_s &= \frac{1}{m_s s + b_s}\end{aligned} \tag{2.3}$$

where m_m and m_s denote the masses of the master and slave robots, and b_m and $b_s$denote the corresponding damping terms.

The PEB-controlled teleoperator in Fig. 2 can be modeled in the hybrid matrix form:

$$\begin{bmatrix} F_h(s) \\ -sX_s(s) \end{bmatrix} = H(s) \begin{bmatrix} sX_m(s) \\ F_e(s) \end{bmatrix} \tag{2.4}$$

with the following hybrid matrix:

$$H(s) = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} Z_m + C_m \frac{Z_s}{Z_s + C_s} & \frac{C_m}{Z_s + C_s} \\ -\frac{C_s}{Z_s + C_s} & \frac{1}{Z_s + C_s} \end{bmatrix} \tag{2.5}$$