FPAA-based Control of Bilateral Teleoperation Systems

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Abstract: Discretizing the continuous-time controller of a master-slave teleoperation system can simplify control implementation. However, in teleoperation systems, discrete-time control can cause a performance degradation compared to continuous-time control. In digitally controlled bilateral teleoperation systems, there exist stability-imposed bounds on the gains of the discrete-time controller and the sampling period, and a trade-off between the two. This means that given a sampling period, it is impossible for the discretized controller to have gains above a threshold, which may well be necessary for successful performance of teleoperated tasks requiring highly accurate master-slave position tracking. In a teleoperation system with analog controller, however, stability does not impose any upper bound on the control gains, thus facilitating the performance of tasks that do require highly accurate master-slave position tracking. Inspired by this advantage of analog control, in this paper we develop a Field Programmable Analog Arrays (FPAA) based controller for bilateral teleoperation, which can achieve higher control gain than its discrete-time counterpart. We present the results of a user study measuring the human performance for a task involving flipping a stiff switch through a teleoperation system. We experimentally show that large sampling periods, necessitating low control gains for maintaining stability, lead to unacceptable task performance. We then show that humans can successfully perform the same task with the FPAA-based controller for the teleoperation system.

Key Words: Bilateral teleoperation, stability, discrete-time control, FPAA-based control, task performance

1 Introduction

While digital techniques have liberated control designers from time-consuming analog design, some of the advantages of analog control have been lost [1, 2], which may have significant performance and stability consequences. This paper studies whether a Field Programmable Analog Arrays (FPAA) based controller can achieve better user task performance compared to a digital controller in bilateral teleoperation.

As will be discussed in Section 3, a larger control gain generally leads to a higher teleoperation system transparency and, therefore, improves user task performance. However, when the teleoperation controller is implemented in discrete-time, 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 system performance to the level that a human operator cannot complete tasks successfully.

One way of solving the aforementioned dilemma is to use fast-sampling processors that provide very small sampling periods such as the field programmable gate array (FPGA) [3, 4]. This option will be more expensive than the ubiquitous personal computers, and only shortens the sampling period but does not eliminate the trade-off between the control gain and sampling period fundamentally.

A more affordable way proposed in this paper is to use analog components to implement the teleoperation controller. As the analog control system does not sample data, it fundamentally eliminates the limitation brought by the sampling period. This article discusses whether a bilateral teleoperation system with a FPAA based controller can accomplish tasks requiring high positioning precision and thus high-gain control, while maintaining the system stability.

FPAA is a new type of reconfigurable analog circuits. Among the commercially available devices, the programmable analog arrays from the Anadigm Company are the most popular circuits [5]. In our work, a dynamically programmable Analog Signal Processor (dpASP) AN231E04, a second-generation FPAA from Anadigm, was used. The AnadigmDesigner2 software provides a simple design template for PID control.

This article shows that a bilateral teleoperation system with an FPAA controller can accomplish not only tasks that require low control gains (typically free-motion tasks or tasks involving contact with compliant environments), which can be achieved by a digital controller, but also tasks requiring high positioning precision, which require high-gain control, while maintaining the system stability. The FPAA-based controller provides these benefits without endangering the system stability. This is shown by a user study demonstrating 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

be control sampling.

The paper is organized as follows. The bilateral teleoperation system used in this paper is modeled in Section 2. A detailed discussion of stability conditions for our teleoperation system is presented in Section 3. The experimental teleoperation system and the utilized position control loop are shown in Section 4, followed by the performance comparison of the FPAA-based controller and discrete-time controller in free motion and in a switch-flipping task. Lastly, concluding remarks are given in Section 5.

2 System Modeling

In this section, the bilateral teleoperation system used in the subsequent sections is modeled. We use position-error-based (PEB) control, in which the master robot follows the slave robot's position, and vice versa. The block diagram of a continuous-time PEB bilateral teleoperation system is shown in Fig. 1, and the corresponding discrete-time PEB teleoperation system is shown in Fig. 2. In both figures, 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.
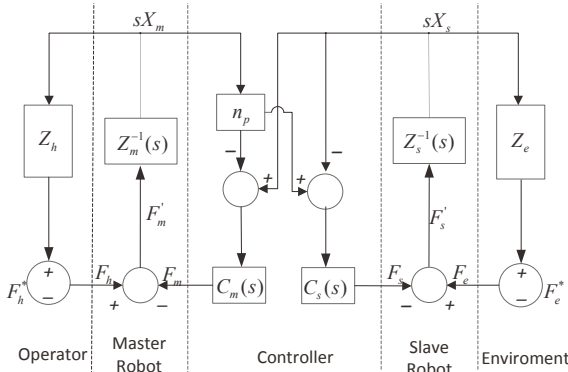

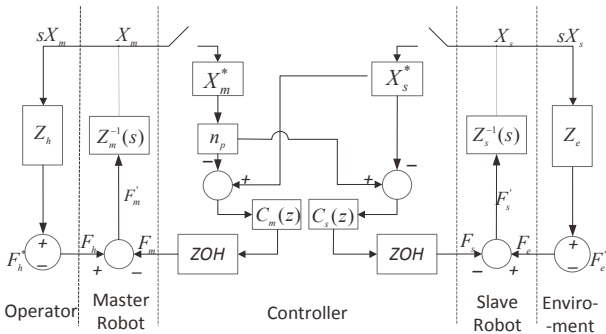Fig. 1: A continuous-time controlled PEB bilateral teleoperation system

Fig. 2: A discrete-time controlled PEB bilateral teleoperation system

The continuous-time controlled PEB teleoperator in Fig. 1 can be modelled in the hybrid matrix form as

$$\begin{bmatrix} F_h(s) \\ -sX_s(s) \end{bmatrix} = H(s) \begin{bmatrix} sX_m(s) \\ F_e(s) \end{bmatrix}, \qquad (1)$$

with the following hybrid matrix [6]:

$$H(s) = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} Z_m + C_m \dfrac{Z_s}{Z_s + C_s} & \dfrac{C_m}{Z_s + C_s} \\ -\dfrac{C_s}{Z_s + C_s} & \dfrac{1}{Z_s + C_s} \end{bmatrix}. \qquad (2)$$

In the above, proportional-derivative (PD) position controllers $C_m = k_{v_m} s + k_{p_m}$ and $C_s = k_{v_s} s + k_{p_s}$ are typically used for the master robot and the slave robot, respectively. Given the use of velocities instead of positions in (1), factors of $1/s$ have been introduced in position controllers.

In Fig. 2, Z_h and Z_e continue to operate in continuous-time. Thus, in the Fig. 1 and Fig. 2, the continuous-time models of the human operator and the environment are:

$$\tilde{F}_h - F_h = Z_h(s)\, s\, X_m ,$$
$$\tilde{F}_e - F_e = Z_e(s)\, s\, X_s , \qquad (3)$$

where s is the Laplace operator.

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

$$sX_m = Z_m(-F_m + F_h) ,$$
$$sX_s = Z_s(-F_s + F_e) , \qquad (4)$$

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:

$$Z_m = \frac{1}{m_m s + b_m} ,$$
$$Z_s = \frac{1}{m_s s + b_s} , \qquad (5)$$

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.

For the discrete-time controllers, the continuous-time signals X_m and X_s are sampled at time instants separated by T [7] as

$$X^*(s) = \sum_{k=0}^{\infty} x(kT) e^{-skT} , \qquad (6)$$

where $*$ shows the sampled signal.

The z-domain equivalent of (3) is $X(z) = X^*(s)\big|_{s=1/T \ln z}$. The Zero-Order-Hold (ZOH) blocks are used to convert the output of the discrete-time controller to continuous-time with the transfer function

$$G_h(s) = \left(1 - e^{-sT}\right)\big/ sT . \qquad (7)$$

For the discrete-time controller designed as in Fig. 2, the sampled-data outputs of the master and slave controllers are [8]:

$$F_m^*(s) = C_m(z)[X_s^*(s) - n_p X_m^*(s)],$$
$$F_s^*(s) = C_s(z)[n_p X_m^*(s) - X_s^*(s)], \qquad (8)$$

where and n_p defines the position ratio between the master and slave robots.

3 Stability and Transparency of a PEB Teleoperation System

3.1 Transparency

In order to obtain satisfactory system transparency and good user performance, correspondence between the master and slave positions and the master and slave forces is required. This amounts to $H(s)$ being as close to

$$H_{ideal} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \qquad (9)$$

as possible. Evidently, condition in (9) would happen in (2) if the gains in the controllers C_m and C_s are large enough. However, as it will be shown Section 3.2, this will pose a problem for stability.

3.2 Stability: Continuous-time Control vs. Discrete-time Control

Having modeled a 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) paves the way for ensuring closed-loop stability via teleoperator absolute stability. A continuous-time absolute stability criterion was proposed by Llewellyn for two-port networks [6, 9], which can be applied to give closed-form conditions involving the teleoperator's hybrid matrix. It is known that the PEB teleoperator of Fig. 1 is absolutely stable if k_{pm}, k_{vm}, k_{ps}, $k_{vs} > 0$ and $C_m(s)/C_s(s) = \alpha$, where α is a positive constant [10].

In the system shown in Fig. 2, which is the sampled-data counterpart of the teleoperation system in Fig. 1, the PD controllers are discretized, e.g., using backward difference method [7], to

$$C_m(z) = k_{vm}(z-1)/Tz + k_{pm},$$
$$C_s(z) = k_{vs}(z-1)/Tz + k_{ps}. \qquad (10)$$

If $k_{vm} = k_{vs} = k_v$, and $k_{pm} = k_{ps} = k_p$, a sufficient stability condition can be found for the sampled-data teleoperator [6] as

$$\frac{b_m b_s}{b_s + b_m} > \frac{k_p T}{2} + k_v. \qquad (11)$$

What is really important is that for a given teleoperation system, the left side of (8) is fixed. Thus, the stability condition puts an upper bound on $k_p T$ and k_v.

3.3 Stability-transparency Trade-off

Based on the above results for the stability and transparency of a PEB teleoperation system, the discrete-time absolute stability condition (11) imposes a trade-off between the sampling period and the proportional gain of the PD controllers. This combined with the

transparency requirements (i.e., high gains in the PD controllers to make (2) approach (9)) show a trade-off between stability and transparency for a fixed sampling period. Indeed, a larger control gain leads to higher transparency but can jeopardize the stability of the sampled-data teleoperation system due to (11). This is in contrast to the continuous-time control case where there is no constraint put on the controller gains by the stability condition, and thus no significant stability-imposed constraint on transparency.

4 Experimental Results

4.1 Experimental setup

Our setup consists of two identical Servo SRV-02 Quick Connect Modules (Quanser Inc., Markham, ON, Canada) as 1-degreee-of-freedom, revolute-joint master and slave robots (Fig. 3). Each of the master and slave modules, which is comprised of a DC motor, a gear, and a potentiometer, is preceded by an *inner* current control loop so that an *outer* position control loop can send torque commands (i.e., F_m and F_s in Fig. 2) to each robot. While the inner current control loop is always implemented by analog components, the outer-loop position controller can be implemented either in the continuous-time or in the discrete-time domain.
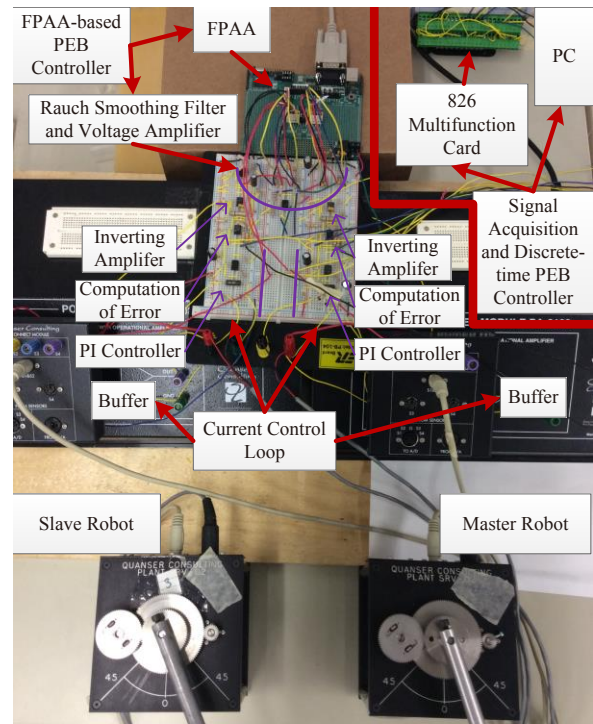

Fig. 3: The experimental setup of the bilateral teleoperation system.

1) Discrete-time Position Control

Digital signals are processed in a PC with a dual-core AMD Opteron Processor 270 at 1.99 GHz with a 64-bit Windows 7 operating system. A Model 826 multifunction analog/digital I/O card (Sensoray Co., Tigard, OR, USA) is used for A/D and D/A conversion. First, the master and slave positions are acquired following A/D conversion of voltages of potentiometers mounted at the robots joints. Next, the

master/slave position error is calculated and fed to the backward-difference discrete-time PD controller in (8) for each of the master and slave robots. Then, following D/A conversion, the control signals F_m and F_s are output to the master and slave robots, respectively. The sampling frequency is 1000 Hz.

2) FPAA-based Position Control

While the previous section discussed the implementation of the position controllers needed in the PEB teleoperation control system in **Fig. 2**, this section shows the same but for the control system in Fig. 1, which operates entirely in the continuous-time.
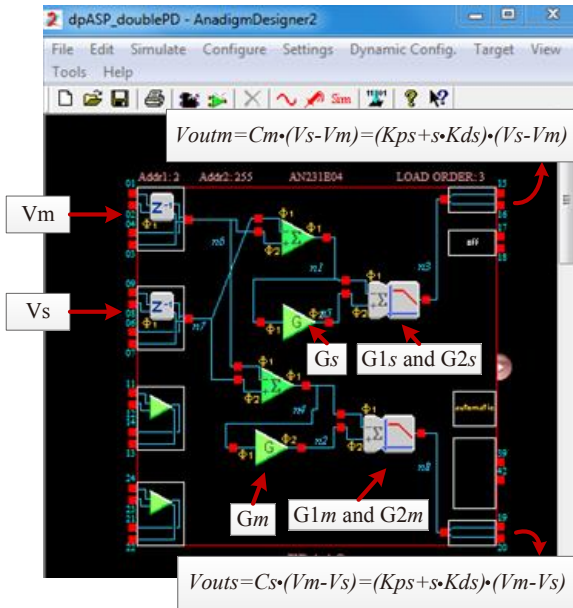

Fig. 4: Circuit realization of a PD controller

Fig. 4 shows a circuit realization of PD controllers using the AN231E04 FPAA device in the professional design software AnadigmDesigner 2.7.1. Each control circuit is composed of these Configurable Analog Modules (CAM):

- SumDiff CAM:
- GainHalf CAM:
- SumFilt CAM:

The master and slave robots positions V_m and V_s (i.e., the voltage readouts from the corresponding potentiometers) are inputs to Fig. 4. Here, K_{pm}, K_{ps} are the proportional gains, and K_{dm}, K_{ds} are the differential gains. G_m, G_s are the gains of the GainHalf CAM for the master robot controller and the slave robot controller, respectively, G_{1m} and G_{2m} are the input gains in the SumFilt CAM in the master side, and G_{1s} and G_{2s} are the corresponding constants in the slave side. The final output voltages are V_{outm} and V_{outs} for two sides, respectively. Overall, assuming a unity gain, the master and slave PD controllers' transfer functions implemented in FPAA will be

$$C_m = K_{pm} + s \cdot K_{dm} ,$$
$$C_s = K_{ps} + s \cdot K_{ds}$$
(12)

4.2 Free motion performance

In our experiments, (9) is used as the stability condition. If the master's and/or the slave's positions become unbounded or oscillate indefinitely, the teleoperation system is judged to be unstable. As explained in Section 3.3, larger control gains are expected to increase the transparency of the teleoperation system. This includes lowering the position error between the master and the slave. The smallest sampling period (i.e., the largest sampling rate) achievable in our system is 1 millisecond (ms), which is used in the following experiments.
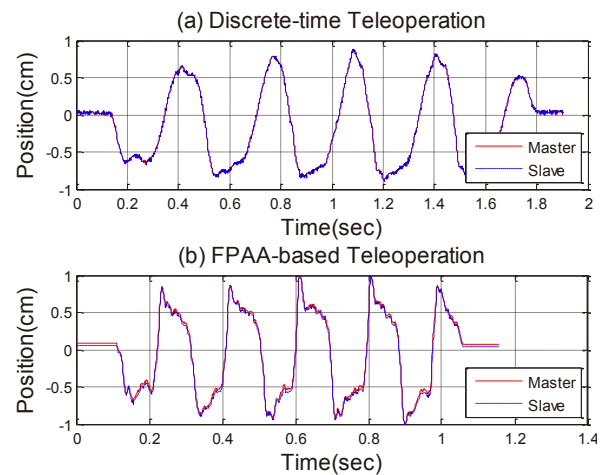

Fig. 5: Comparison of the Master-slave position tracking profiles in two teleoperation systems when the operator moves the master and the slave is in free space.

In Fig. 5, the proportional controller gains are 20 for (a) and 80 for (b), which are both the maximum gains that can be obtained in two systems. The Euclidean norms of the position tracking errors are 0.0826, 0.0685, respectively. It can be seen from Fig. 5 that in both the FPAA-based haptic teleoperation system and the discrete-time teleoperation system, free motion task can be accomplished easily with small position tracking errors. This is not the case, however, in hard contact conditions described next.

4.3 Human Task Performance in Teleoperated Switch Flipping Task

To demonstrate the superior performance of an FPAA-based controlled teleoperation system compared to the case of discrete-time control, let us consider a "stiff" (one requiring high-gain position control) task. Consider a teleoperated switch-flipping task, where the user needs to flip the switch in Fig. 6 from position 1 to position 2 (corresponding to a "success" outcome) but not to position 3 (corresponding to a "fail" outcome). In order to achieve this aim in the teleoperation mode, the master/slave position tracking error, which is influenced by the teleoperation controller performance, should be no more than the distance between positions 2 and 3 of the switch. Evidently, successful user task performance goes hand in hand with
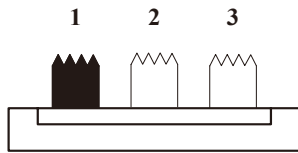
high system transparency for this task.

Fig. 6: A three-way switch

Considering the discussion in Section 3.3, the only way to reach such a small position error is to have a sufficiently large control gain, which may risk instability in the case of discrete-time control.

In the following, the system performance of the discrete-time controlled teleoperation and FPAA-based teleoperation is compared first. The system performance is measured by the master-slave position tracking error, as explained above, which is the key to the successful performance for the switch-flipping task using bilateral teleoperation. Secondly, the human task performances of two teleoperation systems with their maximum gain respectively are investigated to see whether they could meet the requirements of successful task performance while preserving stability.

1) Teleoperation system performance

Fig. 7 shows the master-slave position tracking profiles of the two systems with their maximum control gains under stable conditions. While inputting the same force to the master robot, the position tracking errors obtained between the master robot and the slave robot are 0.02 and 0.18 under FPAA-based and discrete-time control, respectively. Obviously, liberating the teleoperation system from the sampling-imposed limitations in terms of the control gain upper bound has a significant effect on the system performance. In the next section, we will investigate if this also translates into actual task success rates.
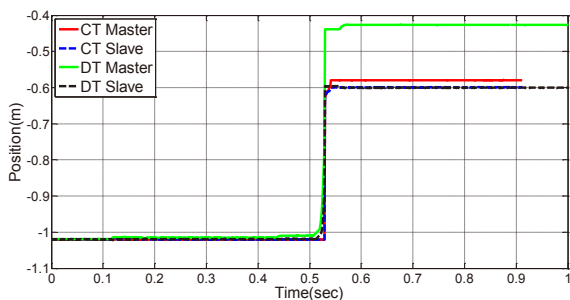

Fig. 7: Position tracking profiles for continuous-time and discrete-time teleoperation under fair comparison conditions

2) Human task performance

Two human operators manipulated the master robot while the slave robot interacted with the switch. The operator's primary goal was defined as flipping the switch in Fig. 6 from position 1 to position 2 but not to position 3 by applying appropriate forces on the master side. Each operator performed two sets of experiments, each comprising of two trials, with a short break between them. Therefore, each user performed 4 trials. In each trial, one of two different

conditions (FPAA-based control, or discrete-time control with a 1 *ms* sampling period) was presented to an operator for doing the switch-flipping task.

The final success rates of human subjects in performing the switch-flipping task, averaged over the 4 trials for each subject, are presented numerically in Table 1. Evidently, the FPAA-based controller resulted in a significantly better tasks success rate compared to the discrete-time controller.

Table 1: Success Task Rates of Different Controllers

Condition⟍ Operator	① C-T controller	② D-T controller with T=1ms
User 1	100%	20%
User 2	100%	20%

5 Conclusions and Future Work

In this article, we showed that an FPAA-based controller can not only accomplish tasks that require low control gains, which can be achieved by a digital controller, but also outperform discrete-time controllers in success rates of tasks requiring high-gain control. Possible extensions of the current study include mixing the capabilities of analog and digital controllers to achieve highly transparent and stable teleoperation in haptic applications involving both soft and hard environments or both force and position control.

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