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Experimental Studies on Improving Safety in Haptic and Teleoperation Systems

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Abstract— **A simplified approach to Time Domain Passivity Control (TDPC) is applied to a haptic teleoperation scheme. Unlike traditional TDPC, this scheme monitors the power output of a port rather than the energy summation. This method differs from traditional TDPC in that it requires no integration and is less subject to the associated problems of reset and data loss. The simplified controller is applied to a number of experiments, and is shown to improve stability and fidelity. The utility of this scheme with respect to safety is extensively.**

I. Introduction

Haptic interfaces are physical systems that link an operator with a virtual environment (VE) which provides physical feedback to the user. When a delay is introduced on the input and output of a haptic interface, the system become analogous to a teleoperation scheme, where a simulated remote environment is manipulated. Haptic systems are subject to oscillatory and otherwise unstable behavior for a variety of reasons, listed in [1]. Introducing delay to the communications signals can also cause instability in an otherwise stable haptic interface [2]. The challenge when designing haptic systems is to find a compromise between transparency and stability.

Many researchers have proposed passivity based solutions to the problem of haptic or teleoperational instability; Hokayem and Spong [3] provide a comprehensive review of these and other stabilizing methods. A passive system, by definition, is one where the energy dissipated by the system is greater than any energy being released from storage in that system. Conversely, an active system is one where some part of a system is adding energy to the overall system. Passivity is an attractive basis for system control as it is a sufficient condition for stability. Also, a networked system is passive if all of its components are also passive.

A problem that arises with many passivity schemes is that, in order to ensure passivity at all times, a constant damping agent is used; this damping value may be too conservative over much of the operational range and reduce performance. Hannaford and Ryu developed Time Domain Passivity Control (TDPC) [4] as a way to identify active system components and remove a corresponding amount of excess energy. The advantage here is that the damping is applied only to parts of the system identified as "active" and that the correction is limited to the amount needed to ensure stability.

TDPC works by monitoring the energy entering and exiting a system node, using what has been termed a passivity observer (PO) (Fig. 1). When the total system energy falls below a specified reference point (typically zero), a passivity controller (PC) is engaged. TDPC has had many variations since its inception [5-7]; many deal with the issue of when to engage the passivity controller.

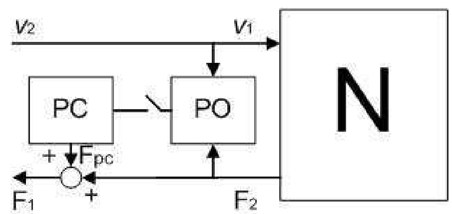

Fig. 1. Single Port with Passivity Observer and Passivity Controller

TDPC has proven to be an effective approach in dealing with instability in haptic or teleoperation systems, however there are drawbacks. Because a traditional TDPC monitors an integrated sum, energy, it is subject to sudden impulsive changes when the summation becomes negative. Simplified time domain passivity control (STDPC), introduced in [9], lessens this problem by monitoring the system power consumption directly. Instead of an energy sum, the power variables are used as a switching criteria to activate the passivity controller. STDPC is simpler to implement, and can be just as effective in many applications.

A typical teleoperated system consists of five components: human operator, master hardware (a force feedback joystick, for example), communications port, slave hardware and environment. The human and environment are considered passive, as any active periods would be temporary and intentional. The master and slave hardware can be modeled as mass-damper systems and can also be considered passive. Although the slave hardware is often controlled to increase fidelity, these controllers can easily be tuned such that they are always passive. The only source of "activeness" is the communication channel.

When a teleoperated system losses stability, it represents not only a failure of control but also a safety concern. For the actuators that provide force feedback to produce a reasonable stiffness they must also be large enough to quickly accelerate the master hardware. This can be hazardous to the operator during periods of instability or runaway conditions in cases where the master hardware is large and bulky, as in Fig. 2.

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Several researchers have attempted to address these safety issues either though hardware [10] or control solutions [1]. STDPC offers a unique solution in that it allows direct limits to the power transmitted to the user. The lack of integration in STDPC is an additional safety feature, as it is not subject to the same issues related to data loss or reset.

In this paper we introduce the concept of STDPC for safety applications and demonstrate the effectiveness of this approach in several related experiments. We also present the first use of STDPC in a teleoperational experiment.

II. Simplified Time Domain Passivity Control

A. Time Domain Passivity Control Review

Unlike the basis for other stability formulas, passivity is defined using the intuitive concepts of power and energy storage. The power (P) entering a one port system (such as in Fig. 1) can be defined as:

$$P = fv = \frac{dE}{dt} + P_{diss}, \quad (1)$$

where f and v are the output force and input velocity, E is the energy stored within the system and P_{diss} is the power dissipated by the system (by friction, for example). Note that for a system starting from rest, $E(0) = 0$ and P_{diss} must be non-negative (otherwise the system is generating energy). The passivity condition states that the integral of the power variable must be positive at all times:

$$\int_0^t P d\tau = E(t) - E(0) + \int_0^t P_{diss} d\tau \geq -E(0), \quad (2)$$

which reduces to :

$$\int_0^t fv d\tau \geq 0. \quad (3)$$

This simply states that the energy entering a passive system must be greater than the energy leaving.

The basic idea behind TDPC is to monitor this energy value in real time and ensure that it never becomes negative by selectively engaging a passivity controller. For a discretely sampled system the passivity observer (PO) is constructed as:

$$PO = \Delta T \sum_{n}^{k=0} f(k)v(k). \quad (4)$$

ΔT is the sampling period and n is the current step. Note that equation (4) represents a numerical integration that must be performed at every time step. If $PO \geq 0$ at any given time, the system connected to the monitored port is dissipating energy and can be considered passive. If the observer falls to a negative value, an adjustable element α is engaged to dissipate the excess energy observed (Fig. 1). The observer monitors exactly how much energy is generated by the unstable port, and this dissipative element removes only the excess amount of energy and is therefore lossless. The PO may also incorporate the environmental energy dissipation if the model is known; more information regarding this may be found in [8].

There are different configurations for the passivity controller depending on whether admittance or impedance causality is used; a complete discussion of the different options is described in [5].

B. Simplified Time Domain Passivity Control

One drawback of traditional TDPC is that it requires numerical integration. This can become an issue if data is lost in transmission or the system is reset and previously stored summation variables are lost. Simplified time domain passivity control does not employ an integration of the power variables; instead it monitors node power consumption directly. The new passivity observer is given as:

$$P_{obsv} = fv - \frac{dE}{dt}, \quad (5)$$

where P_{obsv} is our passivity observer. The E in the $\frac{dE}{dt}$ term is the port-side stored energy, which we assume can be modeled. As with the traditional TDPC, if P_{obsv} falls below zero we can determine that the monitored channel has become active, and the passivity controller (PC) is engaged.

The PC is designed such that $P_{obsv} + P_{ctr} = 0$, where P_{ctr} is the power dissipated by the PC. For a series PC with impedance causality, as in Fig. 1, the power dissipation element is computed as:

1) $v_1(n) = v_2(n)$ is an input;
2) $f_2(n) = F_E$ where F_E is the environtmental force;
3)

$$\alpha(n) = \begin{cases} -P_{obsv}(n)/v_2(n)^2 & \text{if } P_{obsv} < 0 \\ 0 & \text{if } P_{obsv} \geq 0; \end{cases} \quad (6)$$

4)

$$\begin{aligned} f_1(n) &= f_2 + f_{PC} = f_2 + \alpha v_2(n) \\ &= f_2(n) - P_{obsv}/v_2(n) \end{aligned} \quad (7)$$

f_{PC} is the output of the PC. α can be similarly computed for the admittance causality case. This formulation can be found in [9]. The combination of the virtual environment and the passivity controller is passive and stable. Note that the passivity controller must be disabled when $v_2 = 0$ to avoid a singularity, in this case $f_1(n) = f_2(n)$.

III. Experiments

A. Experimental Setup

The apparatus used in these experiments was constructed in-house (Fig. 2). Feedback force on the steering wheel is produced through a direct coupling to a MCG IB34005 brushless DC servo motor with a peak torque of 5.2 Nm. The motor is powered by a BMC12L servo drive, and the command signal is provided by a Quanser Q8 data acquisition card. All input and output signals are transmitted through the Quanser Q8 terminal board. The virtual environment (VE) and controller are constructed in a MATLAB SIMULINK model. WINCON software allows us to connect the motor driver and position feedback signals, via the data aquition card, to blocks in our SIMULINK model. For this experiment a sampling rate of 100 Hz was used. This relatively slow rate for haptic applications was chosen so that we can apply this work to other real-world applications with similar sampling rates in the future. Note that all torque and angle measurements have been converted to force and distance measurements for this paper.

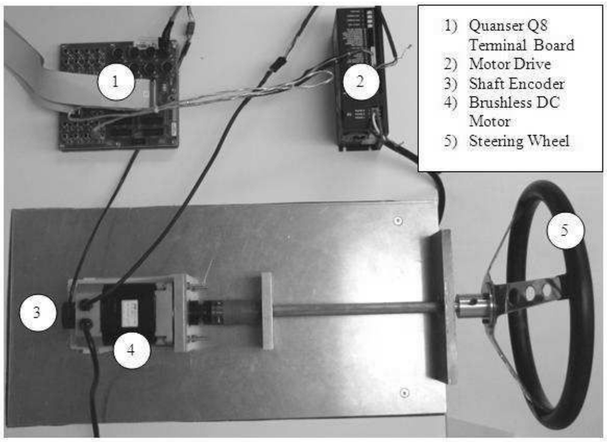

Fig. 2. 1 DOF haptic device

Note the notation for the following equations: x_m, x_s, x_{sd} and x_{sw} refer to the master position, slave position, slave desired position, and spring wall position respectively; velocities are similarly annotated with v.

The slave hardware is a virtual mass-damper system, with a mass of 4 kg and damping of 2 Ns/m, which is controlled with a PI controller:

$$F_{cont} = K_P(v_{sd} - v_s) + K_I(x_{sd} - x_s), \tag{8}$$

where K_P and K_I are 100 and 800 respectively. The slave side environment is modeled as a virtual spring wall positioned at 0.4 m. The force provided by the spring wall is given as:

$$F_e = k_s(x_s - x_{sw}) + b_s(v_s). \tag{9}$$

The spring wall spring contant k_s and damping constant b_s will vary for different experiments. The spring wall does not generate feedback force when $x_s \leq x_{sw}$.

In this experiment, the passivity observer is placed on the master side; it monitors incoming force and outgoing velocity signals originating from between the master hardware and the communications port. This treats the communications port, slave hardware and the VE as one node for passivity observation purposes.

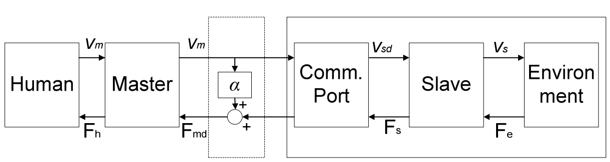

Fig. 3. Teleoperation scheme with master side passivity observer

The energy stored (E_s) in the VE is not available at our master side PO. Instead we substitute the V_m term instead of V_s to derive a reference energy (E_{ref_s}) estimate of the slave side conditions. This reference energy estimate can be expressed as the sum of the kinetic energy of the slave (E_k) and the compressed spring energy (E_{sw}) of the spring wall.

$$\begin{aligned} E_s &= E_k + E_{sw}, \\ &= \frac{1}{2}m_s v_s^2 + \frac{1}{2}k_s(x_s - x_{sw})^2, \end{aligned} \tag{10}$$

$$\begin{aligned} E_{ref_s} &= E_{ref_k} + E_{ref_{sw}}, \\ &= \frac{1}{2}m_s v_m^2 + \frac{1}{2}k_s(x_m - x_{sw})^2, \\ \frac{dE_{ref_s}}{dt} &= m_s v_m a_m + k_s x_m v_m. \end{aligned} \tag{11}$$

The term $k_s x_m v_m$ is eliminated if $x_m < x_{sw}$.

For experiments (2-5) a human input model was used for objectivity. These experiment were also performed with a real human operator, the qualitative remarks below reflect these experiments. The modeled human force, F_h, represents an additive force input sent to the motor:

$$F_h = K_P(x_{hd} - x_m) + K_D(v_{hd} - v_m)dt, \tag{12}$$

where x_{hd} is the desired human trajectory, $K_P = 7$ and $K_D = 5$. This represents a "light touch" human operator; an operator who is partially distracted or not putting a full effort into the teleoperation task. This is an appropriate model for testing with regards to safety concerns.

B. Experiment 1: Free Motion

Using a human operator, the steering wheel was moved around in free space, in such a way that the slave does not make contact with anything in the VE. A constant delay of $T_d = 0.2$ seconds is applied to the forward and return signals. Without any interaction from the VE, the passivity controller never engages, leaving the master controller unimpeded (Fig. 4).

Interestingly, the same experiment was attempted using V_s instead of V_m as the velocity term in the PO (Fig. 5). Likewise x_s is used instead of x_m. This uses an extra communication port to return the actual position from the slave side, rather than the outgoing signal from the master side. Although the passivity controller did dampen the system, it engaged inconsistently, creating noise.

C. Experiment 2: Interaction with an Active Environment

In this experiment, we examined the effects of using STDPC on an active environment. The damping coefficient on the spring wall was made negative (b_s = -10 Ns/m) so that the environment is creating an undesired push in the direction of travel. The desired path of travel was a constant 0.2 m/s velocity towards a desired contact point of 0.5 m; this was impeded by contact with the spring wall at 0.4 m. The spring coefficient for the spring wall in this experiment was set at k_s = 100 N/m.

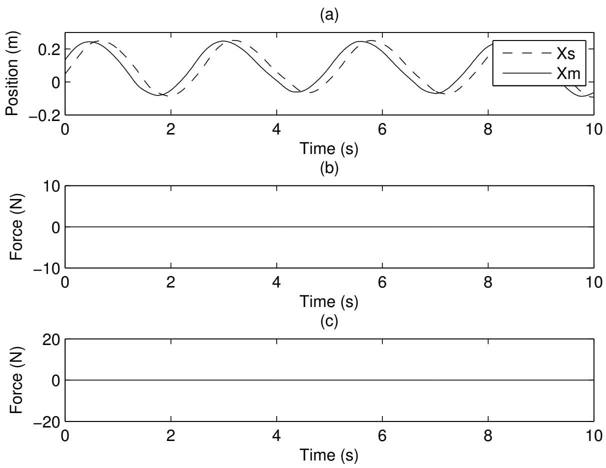

Fig. 4. Free movement using V_m, T_d = 0.2s: a) slave/master position b) feedback force expressed to user c) passivity control force

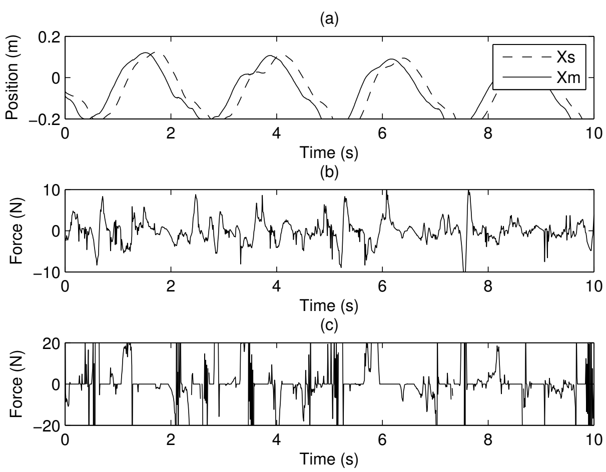

Fig. 5. Free movement using V_s, T_d = 0.2s: a) slave/master position b) feedback force expressed to user c) passivity control force

Without the STDPC it was hard to maintain contact with the spring wall (Fig. 6), the system had a tendency to bounce energetically off the wall. When the PC is allowed to engage (Fig. 7), a single bounce still occurs but the forcefulness of the bounce is much smaller and the probe settles quickly to a state of steady contact.

D. Experiment 3: Delayed Interaction with Remote Environment

In this experiment the input and output signals were delayed through the communication ports by 0.2 seconds. The desired input trajectory was a sine wave of the form: $x_{hd} = 0.3sin(2t) + 0.2$. This periodically put the desired position inside the spring wall, resulting in contact. Here the spring wall contains no damping (b = 0) and has a light stiffness of 100 N/m.

We can see from Fig. 9 that the fidelity of the system

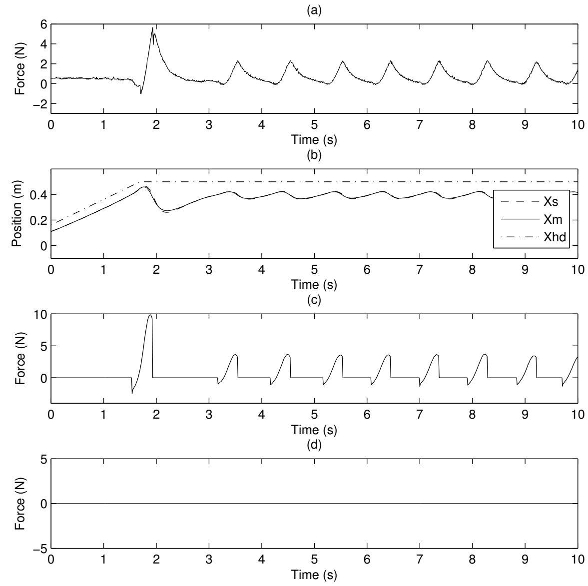

Fig. 6. Interaction with an active environment without STDPC, b_s = -10, no delay: a) human applied force b) slave/master/desired position c) environment force d) passivity control force

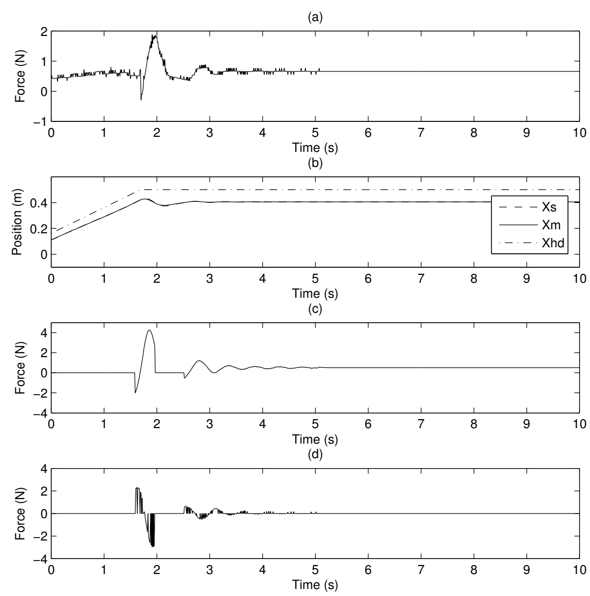

Fig. 7. Interaction with an active environment with STDPC, b_s = -10, no delay: a) human applied force b) slave/master/desired position c) environment force d) passivity control force

was improved by the passivity controller. Without passivation (Fig. 8) the system tended to move sharply away from contact with the wall. This is a result of the force signal always being delayed from the actual contact force. On the spring return the apparent environment force was greater than the actual force. This created the sensation that the user must constantly

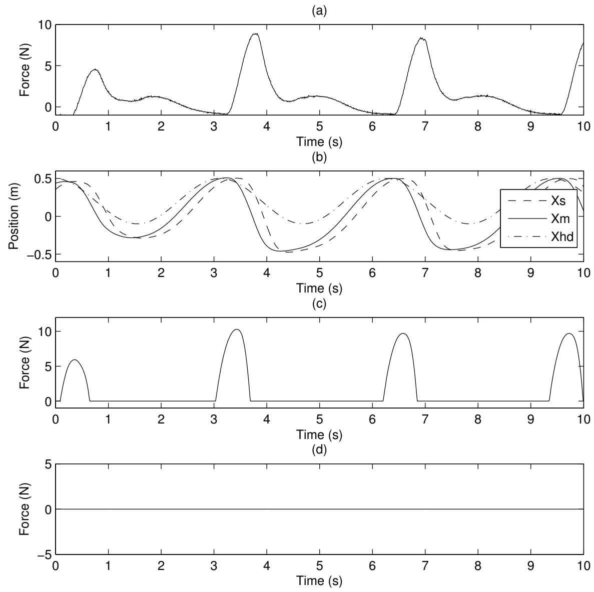

Fig. 8. Delayed probing of a spring wall without STDPC, T_d = 0.2s: a) human applied force b) slave/master/desired position c) environment force d) passivity control force

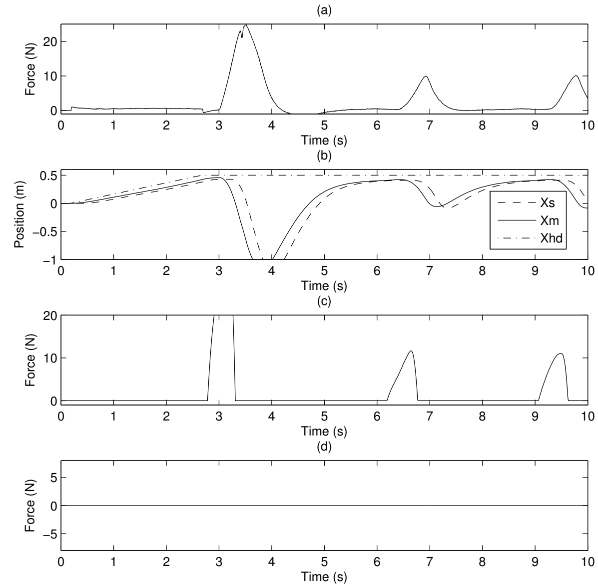

Fig. 10. Delayed contact of a hard surface without STDPC, T_d = 0.2s : a) human applied force b) slave/master/desired position c) environment force d) passivity control force

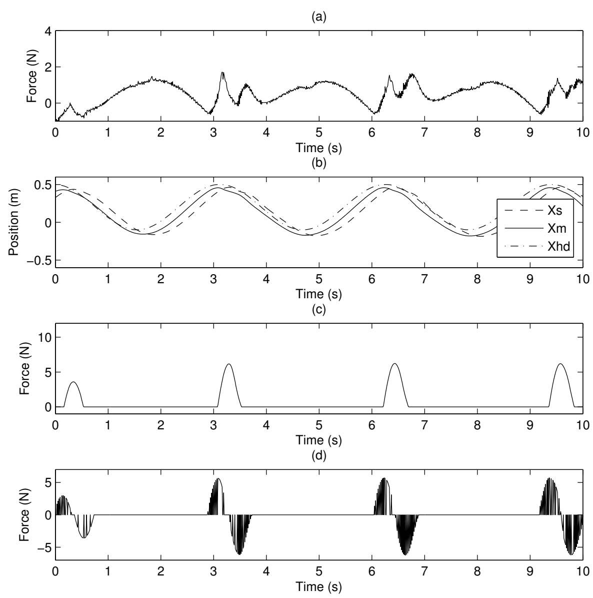

Fig. 9. Delayed probing of a spring wall with STDPC, T_d = 0.2s: a) human applied force b) slave/master/desired position c) environment force d) passivity control force

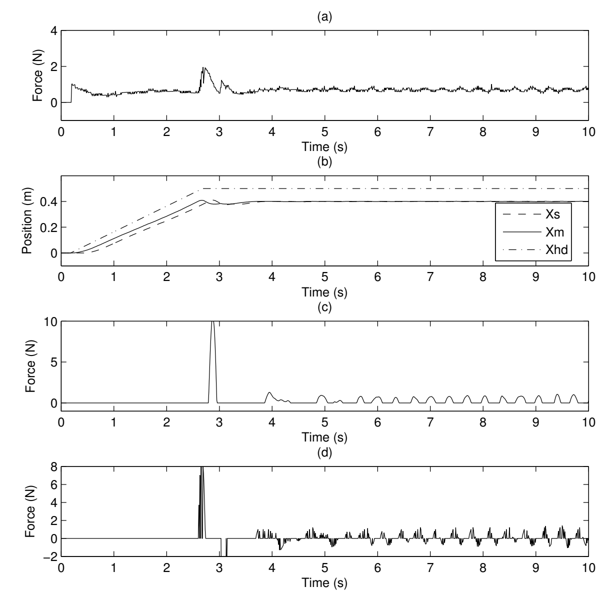

Fig. 11. Delayed contact of a hard surface with STDPC, T_d = 0.2s : a) human applied force b) slave/master/desired position c) environment force d) passivity control force

correct for overshoot.

E. Experiment 4: Delayed Contact of a Hard Surface

Here we attempted to make steady contact with a remote "hard" object (k_s = 1000 N/m, b_s = 0), where the forward and return delays were $T_d = 0.2$ seconds.

At the point of contact the system reacts very aggressively without passivity control (Fig. 10), abruptly increasing the contact force and pushing the master interface quickly away from the point of contact. With STDPC, this behavior was diminished, resulting in only a small force reaction response followed by steady contact, as in Fig. 11.

F. Experiment 5: Parametric Error in the Slave Reference Energy Model

A reference value of the power consumption on the slave side (11) is used by the passivity observer on the master side. We varied the modeled position of the spring wall in the VE, while keeping the actual position fixed at 0.4 meters. This introduced error in the reference energy and thereby changed the instances and duration of PC engagement. We repeated the delayed interaction with a remote environment experiment (Exp. 3), with different modeled positions for the spring wall. The total integrated position error $(x_m - x_s)$ over 11 seconds was calculated for each experiment. This experiment was also repeated without the passivity controller as a reference test.

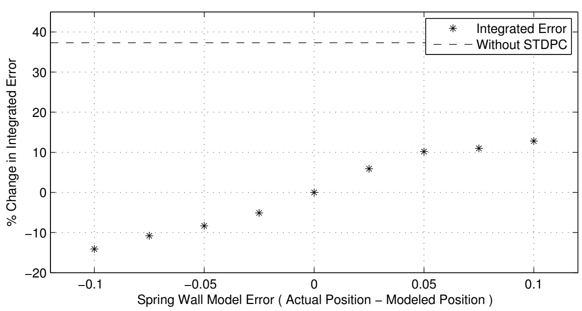

Fig. 12. Effect of uncertainty on master/slave position error: each point represents the average integrated error $(x_m - x_s)$ over 3 trials, - - - represents an average of 3 trials without STDPC

The positional error can actually be improved with mismatch (Fig. 12). As the modeled spring wall position is moved towards the probe, such that the modeled duration of contact is reduced, the positional error decreases. This result is not unexpected; it is similar to adding a damper to a semi-stable system to improve stability. Conversely, moving the modeled spring wall away from point of contact reduces the modeled period of engagement below the actual period and increases overall error. In every case, the total integrated error was less than the case without STDPC.

IV. Discussion and Potential Applications

Safety in haptic and teleoperated interfaces is not well discussed in academic literature; principally because haptic applications are mainly limited to laboratory experiments. Haptic users may, in certain cases, have increased influence over the remote environment and a lessened awareness of remote conditions. The manipulation of remote objects requires a new set of saftey considerations. If haptics are to be used in real-world applications, safety standards will need to be developed. Setting a limit on maximum power transmission, using STDPC, would be one way to ensure safety for a haptic interface.

Even with perfect fidelity and stability, a teleoperated system is potentially dangerous. For instance, a very forceful push from an remote environment on the slave side, such as from a falling object, collision, or explosion, would be dangerous if faithfully transmitted to the user. STDPC could be used to limit transmitted movements to a specified power threshold that could be deemed safe.

Despite parametric uncertainty in the modeled remote side energy, STDPC can still effective at increasing stability. This implies that, in cases where slave environmental parameters are not known, these could be selected using reasonable assumptions, and performance gains may still be made. It also implies that active tuning or some sort adaptive identification of the reference model parameters may lead to even better performance, however this may take away from the simplicity of the approach.

The passivity controller engages only when required and the duration and effects of the controller are well defined. This has potentially useful applications as an intermediary controller when developing or testing new control schemes. The STDPC would only engage in cases where the controller under development fails to keep the system stable.

V. Conclusions

These experiments have shown that STDPC is an effective approach to dealing with instability in active haptic systems, and teleoperation with delay. The main advantage of the STDPC approach is that it is very easy to implement.

As teleoperation and haptic interfaces proliferate in real-world applications, safety will become an increasingly important concern. Simplified time domain passivity control provides a simple method of limiting the hazards of unstable or run-away systems. System power output is a useful safety metric and STDPC is an elegant way of limiting this directly.

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