2012 IEEE International Conference on Robotics and Automation
RiverCentre, Saint Paul, Minnesota, USA
May 14-18, 2012

Stability of Position-Based Bilateral Telemanipulation Systems by Damping Injection

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Abstract— **In this paper two different approaches to guarantee stability of bilateral telemanipulation systems are discussed. Both approaches inject damping into the system to guarantee passivity of the interaction with the device in the presence of time delays in the communication channel. The first approach derives tuning rules for a fixed viscous damper, whereas the second approach employs modulated dampers based upon the measured energy exchange with the device and enforces passivity in the time domain. Furthermore, a theoretical minimum damping injection scheme is sketched that shows that the fixed damping approach is inherently conservative with respect to guaranteeing stability. Experimental results show that both the theoretical minimum damping scheme and a time domain passivity algorithm are successful in stabilizing the telemanipulation system for large time delays with lower gains of the damping elements than derived by the fixed damping injection approach. However, as damping is inherently present in the system, the fixed damping tuning rules can be used to identify if a time domain passivity algorithm is needed given boundary conditions on the actual time delays.**

I. Introduction

Bilateral telemanipulation systems allow users to interact with remote environments and experience some notion of the interaction forces (haptic feedback). The realism of this reflected interaction is called the transparency of the system [1]. The obtainable transparency is amongst others determined by the implemented bilateral control algorithm. A fundamental requirement for a useful telemanipulation system is that it is guaranteed to be stable given all possible circumstances that can be encountered during operation.

There are many different bilateral control algorithms proposed in literature, see e.g. [2] for a recent overview. Each control algorithm is characterized by different transparency and stability properties. In this paper we will compare two methods to ensure stability of a position-position (P-P) bilateral controller, Fig. 1.

When no time delays are present in the communication channel the P-P controller of Fig. 1 is guaranteed to be passive [3] (neglecting the destabilizing influence of sampling [4]). The passivity of the bilateral controller is an attractive property as the interaction between passive systems is guaranteed to be stable. The user and the environment can both be assumed to be passive, or to interact at least in a stable manner with passive systems [5]. It is well-known that time delays can transform passive bilateral controllers that exchange power variables (e.g. velocities and/or forces) into controllers that generate "virtual" energy. This "virtual" energy can in turn potentially destabilize the system. For the P-P controller this has been shown by Artigas et al. [6].

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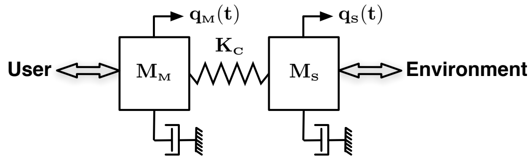

Fig. 1: **Position-based bilateral control:** in the non-delayed situation a single spring is connecting both devices.

Preventing this "virtual" energy from being generated, or to ensure that it is properly dissipated, ensures the passivity of the total telemanipulation system. Anderson and Spong [7] and Niemeyer and Slotine [8] have proposed to use scattering/wave variables to deal with the destabilizing influence of time delays. Applying this coding scheme to the exchanged power variables turns the communication channel itself into a passive element for any constant time delay. However, the inherent nature of the coding operation implies that information is mixed and/or lost and consequently the transparency of the system is reduced [9].

A different approach that is being applied more often is to ensure the stability of bilateral controllers by means of appropriate damping injection. We distinguish two major groups of approaches. The first group applies Lyapunov theory to derive the fixed amount of viscous damping required in the control algorithm to ensure passivity of the bilateral controller under all circumstances, e.g. [3], [10], [11]. The other group applies damping elements which are modulated based on a monitored energy balance of the system. These approaches only add additional damping to the system to maintain passivity according to the energy balance, Time-Domain Passivity (TDP) algorithms e.g. [12], [13]. The applicability of these two approaches to the guaranteed stable interaction with the telemanipulation system will be compared in this paper. For that reason a theoretical Minimal Damping Injection (MDI) scheme is derived.

The paper is organized as follows; Section II introduces the system model. Examples of the fixed damping approach are treated in Section III-A. The MDI scheme is derived in Section III-B. As TDP algorithm the two-layer framework introduced by Franken et al. [17] is used and discussed in Section IV. In this paper an extension to the two-layer framework is proposed and its performance is compared to the fixed damping approaches. Section V contains experimental results obtained with the three approaches. A discussion on the applicability of each approach is contained in Section VI. Finally, conclusions are drawn in Section VII.

II. SYSTEM MODEL

In this paper we will examine two 1 degree of freedom (DOF) devices that are coupled by means of a P-P bilateral controller. Each device consists of a mass, M, and has internal viscous friction, B:

$$\begin{aligned} F_U(t) + F_{Cm}(t) &= M_M\ddot{q}_M(t) + B_M\dot{q}_M(t) \\ F_E(t) + F_{Cs}(t) &= M_S\ddot{q}_S(t) + B_S\dot{q}_S(t), \end{aligned} \tag{1}$$

where $q(t)$ and $\dot{q}(t)$ indicate a position and velocity and the subscripts $_M$ and $_S$ indicate the master and slave device, respectively. $F_U(t)$ and F_E indicate the force exerted by the user and the environment on the devices, respectively. Finally, $F_{Cm}(t)$ and $F_{Cs}(t)$ indicate the forces exerted by the P-P bilateral controller and are defined as:

$$\begin{aligned} F_{Cm}(t) &= -K_{Cm}(q_M(t) - q_S(t)) - B_{Cm}\dot{q}_M(t) \\ F_{Cs}(t) &= K_{Cs}(q_M(t) - q_S(t)) - B_{Cs}\dot{q}_S(t), \end{aligned} \tag{2}$$

where K_C, B_{Cm}, and B_{Cs} are the proportional and derivative gains of the applied position controllers, respectively. This system is depicted in Fig. 1, where for brevity the viscous damping in the devices and the controllers have been combined into B^*_M and B^*_S, respectively.

III. STABILIZATION BY DAMPING INJECTION

The system introduced in the previous section is guaranteed to be stable when no time delays are present in the communication between the master and slave system [3]. The destabilizing influence of time delays can be removed by including an appropriate amount of damping in the system.

The amount of additional damping which is apparent to the user has a large influence on the experienced transparency of the system. DeGersem et al. [14] have already shown that damping experienced by the user significantly reduces the transparency of the telemanipulation system. In order to obtain the highest amount of transparency, the amount of damping added to stabilize the system should be as low as possible. In order to compare both of the approaches mentioned in Section I, the theoretical minimum amount of damping required for passivity of the system is derived in this section.

A. Fixed Damping Injection

Various people have looked into how to stabilize bilateral controllers by means of fixed damping injection. Using a Lyapunov analysis tuning conditions are derived. These conditions link the required damping to the implemented stiffness of the position-controllers and the time delay in the communication channel. Some conditions that have been published in literature are discussed below.

Lee et al. [3] considered the situation in which the implemented stiffness, K_C, and damping, B_C, in the position-controllers and the time delays, T, in the communication channel are constant and symmetric. They derived that the bilateral controller would be guaranteed stable when the following condition was satisfied

$$B_C \geq 2TK_C. \tag{3}$$

Nuno et al. [10] presented a different derivation that removed the necessity of certain assumptions in the work of Lee et al. and relaxed the parameter condition. In their work the following bound was derived:

$$4B_{Cm}B_{Cs} > (\overline{T}^2_{MS} + \overline{T}^2_{SM})K_{Cm}K_{Cs}, \tag{4}$$

where $\overline{T}_{MS}$ and $\overline{T}_{SM}$ are the upper bounds for the time delays in the communication from the master to the slave and vice versa, respectively.

Hua et al. [11] also incorporated asymmetric varying time delays and derived the following linear matrix inequalities:

$$\begin{aligned} -2B_{Cm}I + \overline{T}_{MS}Z + \overline{T}_{SM}K^2_{Cm}S^{-1} &< 0 \\ -\frac{K_{Cm}B_{Cs}}{K_{Cs}}I + \overline{T}_{SM}S + \overline{T}_{MS}K^2_{Cm}Z^{-1} &< 0, \end{aligned} \tag{5}$$

where S and Z are positive-definite matrices and I the identity matrix, respectively. For a one DOF system (5) can be simply rewritten in the form of (4) as

$$2B_{Cm}B_{Cs} > (\overline{T}_{MS} + \overline{T}_{SM})^2 K_{Cm}K_{Cs}, \tag{6}$$

by first isolating B_{Cm} and B_{Cs} in (5) and multiplying those expressions. Evaluating the derivative of the obtained inequality with respect to SZ and taking into account the positive definiteness of both S and Z it follows that the inequality is minimized for $SZ = K^2_{Cm}$ resulting in (6). It follows immediately from (4) and (6) that in this case the result obtained by Hua et al. is more restrictive than that obtained by Nuno et al.

The condition derived by Nuno et al. [10] is a required condition to guarantee stability of the system when any device and any user and/or environment is considered. Therefore it is only dependent on the time delay and the parameter settings.

B. Minimal Damping Injection

In the previous section several parameter conditions have been discussed that stabilize the P-P controller of Fig. 1 in the presence of time delays. In this section, the amount of damping theoretically needed to implement a passive P-P controller, in the presence of arbitrary time delays in the communication channel, will be investigated. For this derivation a P-P controller with symmetric stiffness term is considered, $K_{Cm} = K_{Cs} = K_C$ in (2).

The time delays in the communication channel separate the master and slave system. Instead of a single spring connecting the master and slave system, we obtain two springs, Fig. 2. One spring connects the master device to the time-delayed position of the slave system and the other spring connects the slave device to the time-delayed position of the master system. Due to the time delays the energy content of these two springs

$$H_{Cm}(t) = \frac{1}{2}K_C(q_M(t) - q_S(t - T_{SM}))^2 \tag{7}$$

$$H_{Cs}(t) = \frac{1}{2}K_C(q_M(t - T_{MS}) - q_S(t))^2, \tag{8}$$

can differ with respect to the energy content of the single

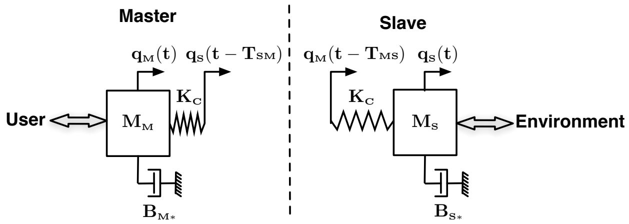

Fig. 2: **Position-based bilateral control with time delay:** Two springs are created in the controller (one at each side). Each spring connects the position of the device at that side to the time-delayed position of the other device.

spring that would connect the master and slave system in the situation without time delays

$$H_C(t) = \frac{1}{2}K_C(q_M(t) - q_S(t))^2. \tag{9}$$

We will consider the difference of (7) and (8) with (9) as "virtual" energy which is generated by the time delays.

This difference in energy content will affect the force exerted by the bilateral controller

$$\begin{aligned} F_{Cm}(t) &= -K_C(q_M(t) - q_S(t - T_{SM}) - B_{Cm}\dot{q}_M(t) \\ F_{Cs}(t) &= K_C(q_M(t - T_{MS}) - q_S(t)) - B_{Cs}\dot{q}_S(t). \end{aligned} \tag{10}$$

The time-delayed position signals can be expressed as the true positions with time-varying difference terms

$$\begin{aligned} q_M(t - T_{SM}) &= q_M(t) + \Delta q_M(t) \\ q_S(t - T_{MS}) &= q_S(t) + \Delta q_S(t). \end{aligned} \tag{11}$$

Thus, using (11), (10) can be written as

$$\begin{aligned} F_{Cm}(t) &= -F_C(t) + K_C\Delta q_S(t) - B_{Cm}\dot{q}_M(t) \\ F_{Cs}(t) &= F_C(t) + K_C\Delta q_M(t) - B_{Cm}\dot{q}_S(t), \end{aligned} \tag{12}$$

where

$$F_C = K_C(q_M(t) - q_S(t)), \tag{13}$$

is the force exerted by the single spring in the no-delay case. Comparing (2) and (10) shows that the influence of the time delays can be represented as an additional component in the force exerted by the bilateral controller on both the master and slave device, $K_C\Delta q_S(t)$ and $K_C\Delta q_M(t)$, respectively.

It is now important to note that the "virtual" energy present in each spring can either be positive or negative depending on the particular motions of the master and slave device and the time delay in the communication channel. If both systems are stationary the "virtual" energy in each spring will eventually become zero (as soon as the value of the stationary position has passed through the communication channel). Only when the "virtual" energy is positive in a spring and energy is injected by that spring into the physical world (the user/environment), "virtual" energy is leaking into the physical world which might destabilize the system.

Positive "virtual" energy is present when:

$$\frac{1}{2}K_C(q_M(t) - q_S(t))^2 < \begin{cases} \frac{1}{2}K_C(q_M(t) - q_S(t - T_{SM}))^2 \\ \frac{1}{2}K_C(q_M(t - T_{MS}) - q_S(t))^2 \end{cases}, \tag{14}$$

which can be expressed in the following two conditions:

$$\Delta q_S(t)(q_S(t) - q_M(t)) + \frac{1}{2}\Delta q_S(t)^2 > 0 \tag{15}$$

$$\Delta q_M(t)(q_M(t) - q_S(t)) + \frac{1}{2}\Delta q_M(t)^2 > 0, \tag{16}$$

which indicates that additional damping is needed when one or both devices are moving towards and approaching the position of the other device. The proximity that the devices need to obtain with respect to each other in order to generate positive "virtual" energy depends on the velocity of the devices and the time delay.

Dissipating the amount of "virtual" energy that would be leaking into the physical world by an additional dissipative element, ensures passive behavior of the spring-coupling between the master and slave under all possible circumstances. From (12) it follows that the dissipative force to achieve this is the force that compensates the additive term due to the time delay. Furthermore, based on the reasoning above, this dissipative term should only be added when "virtual" energy is injected into the physical world by the spring, so

$$\begin{aligned} F_{Rm}(t) &= \begin{cases} -K_C\Delta q_S(t) & \text{if (15) and } -F_{Cm}(t)\dot{q}_M(t)<0 \\ 0 & \text{otherwise} \end{cases} \\ F_{Rs}(t) &= \begin{cases} -K_C\Delta q_M(t) & \text{if (16) and } -F_{Cs}(t)\dot{q}_S(t)<0 \\ 0 & \text{otherwise.} \end{cases} \end{aligned} \tag{17}$$

The corresponding damping coefficients, B_{Rm} and B_{Rs}, of the corresponding modulated dampers are

$$B_{Rm} \leq \frac{K_C\Delta q_S(t)}{\dot{q}_M(t)} \text{ and } B_{Rs} \leq \frac{K_C\Delta q_M(t)}{\dot{q}_S(t)}, \tag{18}$$

where $\leq$ indicates that the required additional damping can be zero (17).

Adding the additional damping force of (17) to (10) enforces passivity of the spring-elements in the controller. Pure spring-elements are passive, but marginally stable and will therefore exhibit an oscillatory response. Asymptotic stability of the system is obtained due to additional viscous damping present in the system (non-zero B_M, B_{Cm}, B_S, and B_{Cs}) as the system will be strictly passive. If desired, part of that additional viscous damping could be used as partial fulfillment of (18).

Naturally this is a purely theoretical result as it is impossible to obtain $\Delta q_M(t)$ and $\Delta q_S(t)$ in a realistic time-delayed telemanipulation application. It does however show that the minimal required damping is not only dependent on the stiffness and the time delays, but also on the relative motions of the devices. In the fixed damping injection approaches arbitrary motions of each device are assumed. However, in reality the motions of the devices are influenced by the user, the environment and the device characteristics. This influence is neglected in the Lyapunov-based analysis of Section III-A. The resulting tuning rules must hold for all possible combinations of impedances and are therefore restrictive by nature as they have to consider the worst case situation of the relative motion of the devices.

The impedances of the user and the environment are non-linear, time-varying, and difficult to model at the least. For that reason they are often assumed to be unknown. However, their influence is present in the interaction with the devices, which can be measured. In the next section we will treat a TDP algorithm that uses this measured interaction data in order to determine a required amount of damping.

IV. Time-Domain Passivity

A different approach to stabilizing the system of Section II is presented by monitoring the energy balance of the system and applying damping only when required by the energy balance. The first of such approaches was the Time-Domain Passivity Control (TDPC) algorithm by Ryu et al. [15].

The energy balance of the system, H, is composed of the physical energy exchange at the master and slave side, H_{Im} and H_{Is}, respectively[1]:

$$H(\overline{k}) = H_{Im}(\overline{k}) + H_{Is}(\overline{k}). \tag{19}$$

The physical energy exchange during a sample period can be computed exactly *a posteriori* of the sample period for impedance-type displays as [16]:

$$\begin{aligned}\Delta H_I(k) &= \int_{(k-1)\Delta T}^{k\Delta T} -F_A(\overline{k})\dot{q}(t)dt \\ &= -F_A(\overline{k})\Delta q(k),\end{aligned} \tag{20}$$

where F_A and $\dot{q}$ are the force and velocity associated with the interaction point between the physical world and the controller in discrete time, e.g. the forces exerted by the control algorithm. (20) represent the energy which is supplied by the actuators at that side. so that

$$H(\overline{k}) = \sum_{i=1}^{k-1} \Delta H_{Im}(i) + \Delta H_{Is}(i), \tag{21}$$

where $\Delta H_{Im}(i)$ and $\Delta H_{Is}(i)$ are the energy exchange at the master and slave side during sample period $\overline{i}$, respectively. Both $\Delta H_{Im}(i)$ and $\Delta H_{Is}(i)$ are computed as (20).

If (21) becomes negative "virtual" energy is generated according to the TDPC algorithm. A modulated damper is activated to dissipate the generated "virtual" energy and restore passivity of the system. This implementation requires instantaneous knowledge of $\Delta H_{Im}(k)$ and $\Delta H_{Is}(k)$. As such it cannot be applied in time-delayed telemanipulation systems. A time-delayed formulation of the TDPC algorithm has been proposed by Ryu et al. [12] and applied by Artigas et al. [6] to the P-P controller in the presence of time delay.

In this paper we will implement the two-layer framework as proposed by Franken et al. [13], which is a different TDP algorithm. The framework consists of two control layers in a hierarchical structure, the *Transparency Layer* and the *Passivity Layer*, see Fig. 3. First the working of the *Passivity Layer* will be discussed. In [13] and [17] it was stated that any bilateral controller could be implemented in the

[1]Notation used in this paper: The index k is used to indicate instantaneous values at the sampling instant k and the index $\overline{k}$ is used to indicate variables related to an interval between sampling instants $k-1$ and k.

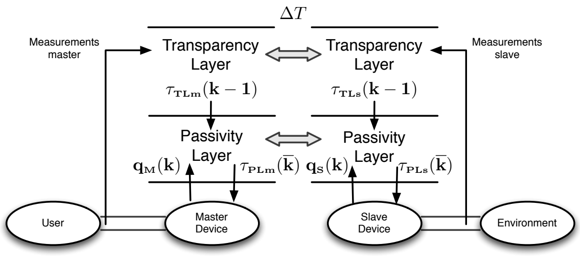

Fig. 3: **Two-layer algorithm for bilateral telemanipulation introduced in [13], [17].** The double connections indicate physical energy exchange.

Transparency Layer given the implementation of the *Passivity Layer* in those papers. However, with a P-P controller implemented in the *Transparency Layer* a modification in the *Passivity Layer* is required. This modification will be discussed in Section IV-B.

A. Passivity Layer

This layer enforces passivity of the bilateral telemanipulation system. When necessary the commands originating from the *Transparency Layer* are adjusted to maintain passivity. In the two-layer framework the energy balance of the system (21) is split into three components

$$H(\overline{k}) = H_M(\overline{k}) + H_C(\overline{k}) + H_S(\overline{k}), \tag{22}$$

where H_M, H_C, and H_S represent the energy present at the master side, the energy in the communication channel, and the energy at the slave side, respectively.

The energy at the master and slave side is stored in energy tanks and these tanks can exchange energy through the communication channel. There are three energy flows connected to each tank:

- Energy exchanged with the physical world, ΔH_{Im} and ΔH_{Is},
- Energy received from the communication channel, $\Delta H_{SM+}(k)$ and $\Delta H_{MS+}(k)$,
- Energy send into the communication channel, $\Delta H_{MS-}(k)$ and $\Delta H_{SM-}(k)$.

The energy flow received from the communication channel at the master side, ΔH_{SM+}, is the time-delayed energy flow sent into the communication channel at the slave side, ΔH_{SM-}, and vice versa. The level of the energy tank at each side is corrected each sampling instant with respect to these three energy flows. The change of the energy level in the master and slave tank, ΔH_M and ΔH_S, respectively, is given as

$$\begin{aligned}\Delta H_M(k) &= \Delta H_{Im}(k) + \Delta H_{SM+}(k) - \Delta H_{MS-}(k) \\ \Delta H_S(k) &= \Delta H_{Is}(k) + \Delta H_{MS+}(k) - \Delta H_{SM-}(k),\end{aligned} \tag{23}$$

and thus

$$\begin{aligned}H_M(\overline{k+1}) &= H_M(\overline{k}) + \Delta H_M(k) \\ H_S(\overline{k+1}) &= H_S(\overline{k}) + \Delta H_S(k).\end{aligned} \tag{24}$$

The energy exchange between the two tanks is determined by the implemented Energy Transfer Protocol. In this paper we will use the Simple Energy Transfer Protocol (SETP) in which each side transmits each iteration a fraction, β, of its available energy to the other side:

$$\Delta H_{MS-}(k) = \begin{cases} \beta H_M(\overline{k-1}) & \text{if } H_M(\overline{k-1}) > 0 \\ 0 & \text{otherwise,} \end{cases} \tag{25}$$

and (25) is likewise defined at the slave side to compute $\Delta H_{SM-}(k)$. This means that $\Delta H_{MS-}(k) \geq 0$ and $\Delta H_{SM-}(k) \geq 0$. The stability properties of the SETP have been analyzed in [17]. The SETP ensures passivity of the communication channel as (assuming zero initial energy in the communication channel):

$$\begin{aligned} H_C(\bar{k}) = \sum_{i=0}^{k-1} & \Delta H_{MS-}(i) + \Delta H_{SM-}(i) \\ & -\Delta H_{SM+}(i) - \Delta H_{MS+}(i) \geq 0. \end{aligned} \tag{26}$$

A Tank Level Controller (TLC) is defined at the master side to regulate the energy level in the system. The TLC is located at the master side as the user has to inject energy into the system for the slave device to be able to execute the commanded task. The TLC is implemented as a modulated viscous damper, that is activated when the energy level in the tank available during sample period $\overline{k+1}$, $H_M(\overline{k+1})$, drops below the desired level of the tank, H_D. The additional force, F_{TLC}, exerted by this modulated damper will extract additional energy from the user during sample period $\overline{k+1}$ to replenish the energy tank, and is given by

$$F_{TLC}(k) = -B_{TLC}(k)\dot{q}_M(k) \tag{27}$$

$$B_{TLC}(k) = \begin{cases} \alpha(H_D - H_M(\overline{k+1})) & \text{if } H_M(\overline{k+1}) < H_D \\ 0 & \text{otherwise,} \end{cases}$$

where $B_{TLC}(k)$ is the modulated viscous damping coefficient, $\dot{q}_m(k)$ is the velocity of the master device at sample instant k and α is a tuning parameter for the rate at which the additional required energy is extracted from the user. $F_{TLC}(k)$ is added at the master side to the feedback force in the *Transparency Layer*, whereas at the slave side the force computed by the *Tranparency Layer* is simply applied to the actuators. The energy tanks in this scheme can be regarded as energy budgets from which controlled motions of the devices can be powered. When the available energy is low, the forces that can be exerted by the devices are restricted. This function has not been used in this paper, but the manner in which the forces are restricted can be designed to suit a specific device, environment, and/or task, [17].

At each side passivity is enforced with respect to the energy tank at that side, which means

$$\begin{aligned} H_M(\bar{k}) &\geq 0 \quad \forall \bar{k} \\ H_S(\bar{k}) &\geq 0 \quad \forall \bar{k}. \end{aligned} \tag{28}$$

This means that passivity of the entire telemanipulation system, (19), is guaranteed, independent of the time delay, as the amount of energy in the communication channel, H_C, due to the SETP can only be positive (26).

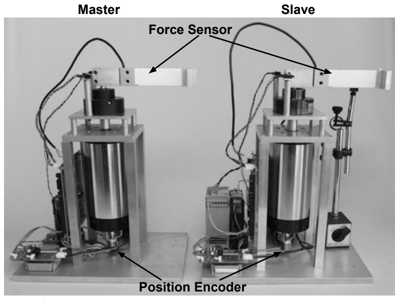

Fig. 4: **Experimental setup:** The setup consists of two identical one DOF lightweight devices.

B. Modification

The *Passivity Layer*, as described in the previous section, enforces passivity of the bilateral system. However, with a P-P controller implemented in the *Transparency Layer* this implementation of the *Passivity Layer* is susceptible to a build-up effect. When the user executes a motion the energy that is injected into the system far exceeds the energy required at the slave side to execute the same motion. This is due to the inherent phase lag in the position response of the slave which influences the feedback force to the user. This mismatch in energy produces a build-up in the energy balance, which hinders the *Passivity Layer* from effectively stabilizing the system.

The user injects more energy into the system than is required at the slave side. This excess energy can be removed by an additional dissipation action is included in the *Passivity Layer* at the master side. If the tank level exceeds the desired tank level, the excess energy is dissipated:

$$H_M(\overline{k+1}) > H_D \Rightarrow H_M(\overline{k+1}) = H_D. \tag{29}$$

V. Experiments

In this section experimental results will be presented for the approaches discussed in Section III-B and Section IV. The experiments are carried out with the setup in Fig. 4. The setup consists of two identical one DOF lightweight devices with low internal friction powered by a DC motor without gearbox. The continuous torque that these motors can exert is $1.38\,\mathrm{Nm}$. A high-precision encoder with $65\,\mathrm{k}$ pulses per rotation is used to record the position of each device.

Both devices are controlled from the same embedded controller running a real-time Linux distribution. The controllers are implemented in the program 20-sim [18] and real-time executable code specific for this setup is generated directly from 20-sim and uploaded to the embedded controller by means of the program 4C [18]. The sampling frequency of the control loop is $1\,\mathrm{kHz}$.

The P-P controller is implemented as (10). A symmetric constant time delay is implemented in the communication

TABLE I: Parameter values in control algorithm

Parameter	Value	Parameter	Value
K_C	$3.75\,\mathrm{Nm/rad}$	B_C	$0.06\,\mathrm{Nm{\cdot}s/rad}$
H_D	$0.2\,\mathrm{J}$	α	$50\,\mathrm{Nm{\cdot}s/rad{\cdot}J}$
β	0.01		

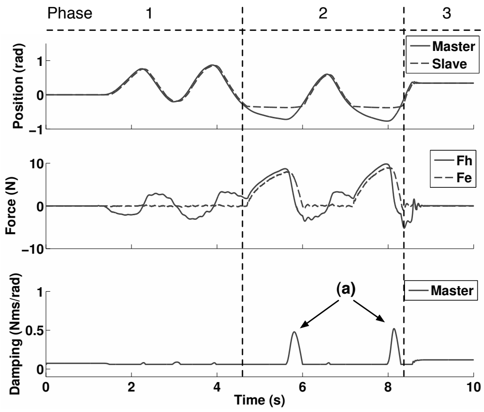

Fig. 5: **Two-layer implementation with 20ms RTT:** A small amount of damping is added at the end of a contact phase (a).

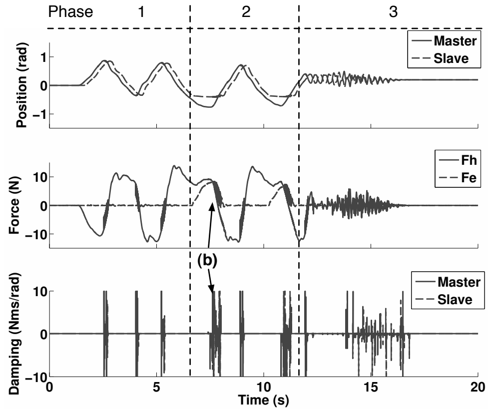

Fig. 6: **MDI implementation with 400ms RTT:** The MDI stabilizes the system, but is susceptible to switching effects (b).

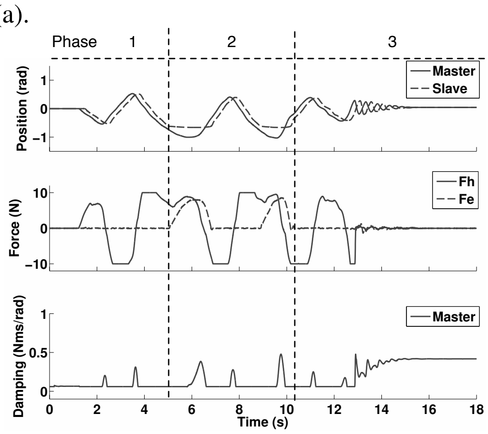

Fig. 7: **Two-layer implementation with 400ms RTT:** Small amounts of additional damping are added when the user reverses motion.

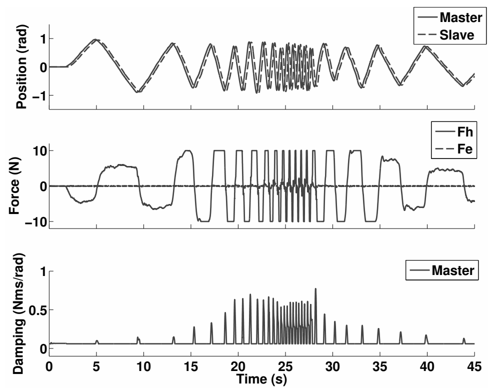

Fig. 8: **Influence of relative motion in the two-layer implementation at 400ms RTT:** The additional damping is dependent on the relative motion.

channel, chosen as 20ms round-trip time delay (RTT) and 400ms RTT. All parameters used in the control algorithm are listed in Table I. Experimental results will be demonstrated with the P-P controller extended with either the MDI approach or the TDP algorithm of Section III-B and Section IV, respectively.

The implemented TDP algorithm adds additional damping only at the master side. For comparison purposes we compute the required damping according to the least conservative approach of Section III-A. The required damping at the master side according to (4) for a delay of 400ms RTT is:

$$B_{Cm} > 4.69\,{}^{\mathrm{Nms}}/_{\mathrm{rad}}. \tag{30}$$

It should be noted that this results from the condition $B_{Cm}B_{Cs} > 0.28$ and that therefore the damping could be distributed over the master and slave system. In reverse, the parameters listed in Table I according to (4) guarantee asymptotic stability of the system for $T < 22.6\,\mathrm{ms}$.

Each experimental plot shows the position of both the master and slave device, the environment force and the force experienced by the user, and the additional damping applied by either the MDI or TDP algorithm, respectively. Phase 1 indicates free space motion, in phase 2 contact with a spring of $1500\,{}^{\mathrm{N}}/_{\mathrm{m}}$ is made twice, and in phase 3 the master device is released by the user during a motion.

In the first experiment, Fig. 5, the TDP algorithm is used in the presence of a communication delay of 20ms RTT. Fig. 5 shows that the influence of the TDP algorithm is minimal during phase 1. In phase 2 damping is added at the end of each contact phase. Therefore, the implemented modification presented in Section IV-B is slightly conservative as this damping is not required. The P-P controller itself is ensured to be passive according to (4), $T = 10\,\mathrm{ms} < 22.6\,\mathrm{ms}$. Finally, during phase 3 the positions of both devices converge.

For the remainder of the experiments the communication delay is increased to 400ms RTT. For this delay the regular bilateral controller becomes unstable when the user does not apply a firm grasp on the device (added damping). It should be noted that for this amount of time delay the transparency of the system is very low and only during phases where both devices are stationary accurate force reflection occurs.

Fig. 6 shows the system response when the regular controller is extended with the MDI algorithm of Section III-B. The MDI ensures that the system is strictly passive and thus that the position of both devices synchronize when the user releases the master device. Fig. 6 shows that the gains of the modulated dampers, resulting from the MDI algorithm, can be extremely large. However, the magnitude of the applied force by the MDI algorithm is always limited, but such a force is also applied when the velocity of the devices is very low and thus the resulting gain becomes very high. Fig. 6 also shows that the MDI algorithm is subject to switching effects which severely decrease the transparency of the system. Therefore, the performance of the MDI with respect to transparency is limited, but it does stabilize the system during phase 3.

The TDP algorithm of Section IV also computes a varying damping gain and is successful in guaranteeing stability of the system during all phases. Fig. 7 shows that the magnitude of the damping gain is very limited compared to (30). Furthermore, Fig. 7 shows that the additional damping is only applied when the user reverses the motion of the master device so that both devices are moving towards each other. This is in accordance with the analysis of when damping has to be applied of Section III-B.

In the last experiment the influence of the motion initiated by the user relative to the time delay on the TDP algorithm is investigated. Fig. 8 shows that the damping computed by the TDP algorithm is dependent on the relative motion of the devices and the time delay. When the user moves very slowly almost no additional damping is applied. For faster movements of the master system the additional damping by the TDP algorithm increases. This is also in accordance with the analysis of Section III-B.

VI. Discussion

In the previous section it was shown that both the MDI scheme and the TDP algorithm were capable of stabilizing the system in the presence of time delays with minimum amounts of additional damping. As the amount of apparent damping for the user should be minimized to provide the best possible transparency it can be postulated that a TDP algorithm is better suited, compared to the fixed damping approach, to stabilize a telemanipulation system in the presence of time delays.

However, the conditions listed in Section III-A can be used to compute an upper bound for the time delay based on the device damping and control parameters. If it can be guaranteed that the time delay will be below the computed bound, the system is already guaranteed to be stable by the damping present and no additional measures are needed. If the time delay exceeds the computed upper bound a TDP algorithm could be implemented to guarantee stability of the system while minimizing the added damping. The conditions of Section III-A serve the purpose of design checks on when the added complexity of a TDP algorithm is justified.

A critical note on the above reasoning is that P-P controllers are ill-suited to deal with time delays from a transparency point of view. Therefore, the implication of the above reasoning on the design of practical telemanipulation systems can be debated as this type of controller is unlikely to be applied in an application with severe time delays.

VII. Conclusions

In this paper two methods to stabilize a position-based bilateral controller in the presence of arbitrary time delays were analyzed and compared to a third theoretical method that implements minimal damping. It was found that the fixed damping approaches neglect the influence of important factors on the amount of damping required to stabilize the system. Therefore, the resulting conditions can be regarded as conservative. The application of a TDP algorithm results in the addition of smaller amounts of damping, which benefits the obtainable transparency. The derived parameter relations can be used as a design check on when the time delay justifies the added complexity of a TDP algorithm. Future work will focus on deriving a modification of the *Passivity Layer* that is less conservative than (29).

Acknowledgment

The authors would like to thank Jordi Artigas of the German Aerospace Center Institute of Robotics and Mechatronics for his suggestions with respect to the structure of the paper.

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