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Proxy-based Approach for Position Synchronization of Delayed Robot Coupling Without Sacrificing Performance

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Abstract— **The application of the position-position architecture for enabling position synchronization of two robotic agents has been proven effective in the fields of telemanipulation and rendezvous of autonomous vehicles. Nevertheless, the approaches presented to this date with the purpose of rendering the position-position architecture passive under the presence of time-delays and packet-loss are only partially able to fulfil that goal. This owes to the fact that they mostly focus on passivating the system, at the cost of transparency. Such an issue becomes even more critical in the presence of position drift caused by most passivation methods. This paper presents a novel control approach that enhances the position synchronization of agents suffering from delayed coupling, by introducing a local proxy reference to one of the agents and only closing the feedback loop when it can preserve stability. The concept is free of position drift and promises less conservatism, without having any prior information about system parameters or prior assumptions regarding time-delay. It has been experimentally validated for time-varying round-trip delays of up to $2s$.**

Telerobotics and Teleoperation, Physical Human-Robot Interaction, Robust/Adaptive Control of Robotic Systems, Haptics and Haptic Interfaces

I. INTRODUCTION

Teleoperation is a crucial tool for performing robotic tasks in remote scenarios. By adding a human operator to the loop instead of having a fully autonomous robot, many of the task requirements, especially in the fields of perception and cognition, can be bypassed. On the other hand, the stability of the task becomes more critical since state and control variables have to be exchanged between remote and operation sites. Since this cannot be accomplished without the addition of time-delays and packet-loss to the loop, additional techniques have to be applied in order to prevent these phenomena from destabilizing the system. In the last decades, vast extent of works have proposed new approaches to tackle the aforementioned issue. Thereamong, passivity based methods, like wave variables [1], [2], energy tanks [3], and the Time Domain Passivity Approach (TDPA) [4], stand out due to their robustness and valuable properties, e.g. it is applicable to linear and non-linear systems, it is a sufficient condition for stability, and it only uses input/output information independent of system parameters. In addition to teleoperation [5], these approaches were successfully applied to a number of other application, including control of series elastic actuators [6], [7], multi-rate control [8], [9], mobile robotics [10], whole-body hierarchical control [11], [12], and explicit force control [13], [14], to name a few.

Absolute stability has been used to allow the teleoperator to be non-passive as long as the closed-loop stability of the teleoperation system is preserved [15]. Llewellyn's criterion [16] can guarantee the absolute stability of a continuous-time two-port network. Although these approaches alleviate the passivity conservatism of the teleoperator, their sufficient condition is represented in frequency domain which requires system parameters that may not be available in many practical implementations. Based on counter-clockwise hysteresis behavior of time-delayed communication channel, the Input-to-State stable approach [17] was applied to each transmitted signal to bound the energy generated due to delay. The ISS can only stabilize time-delayed teleoperation system with known and unvarying time-delays.

The foremost requirement for a delayed bilateral teleoperation is stability, which is achieved by most of the control approaches at the cost of reduced performance, e.g., force mismatch and position offset between haptic input device and remote robot. The issue of unintuitive force feedback was tackled in [18] by preserving the physical coupling behavior on the input device side despite communication delay. When it comes to time-delayed position synchronization, a number of approaches have been proposed. In [19], the passive-set-position modulation (PSPM) proposed to store the energy dissipated by the virtual damper in an energy tank and later introduce it into the system without infringing the continuous-time passivity condition. However, the effects of sampling are partially ignored and can cause instability if Colgate's passivity condition [20] is not fulfilled. A solution to that issue was proposed in [3]. However, there remains the necessity of performing premovements in order to ”charge” the energy tank multiple times, which can increase the physical and psychological burden of the task. In [21] a wave-variable approach to allow position synchronization of two agents was introduced. Nevertheless, problems arise in terms of the transparency of the task [22], which, in addition to damping out energy based on a worst-case scenario, suffers from wave reflection issues.

Moreover, in [23], a TDPA-based approach was proposed in order to passivate a position-position teleoperation architecture. However, despite ensuring passivity in an adaptive

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way, which is an advantage over wave-variable methods [24], that approach suffers from position drift. To tackle that issue, two types of solutions have been proposed. Add-on drift compensators for TDPA were proposed in [25], [26], [27] and extended to multi-DoF telemanipulation in [28]. Notwithstanding, drift compensation depends on the presence of so-called passivity gaps, which are rare for high delays. On the other hand, a modification of TDPA based on r-passivity was proposed in [29], which does not suffer from position drift. However, since the approach is based on power-based TDPA, its conservatism limits the allowed force feedback, and thus the transferred impedance. In that case, position synchronization comes at the cost of further increased discrepancy between the impedance of the local and the remote task.

This paper presents a novel approach that guarantees stability while removing position drift and enhancing transparency between two agents connected in a position-position (P-P) architecture with an unknown time-varying communication delay. The proposed approach decouples the two agents in a way such that Agent1 directly influences Agent2, but Agent2 has an indirect influence on Agent1 through the introduction of another proxy agent. This proxy will try to track the delayed information of Agent2 as accurately as possible, but only as long as asymptotic stability of Agent1-proxy subsystem is not jeopardized. Assuming Agent2 has a stable reference following controller where the reference is the delayed position from Agent1, therefore if Agent1 stops, Agent2 would also converge at its delayed reference position. Thus, if Agent1-proxy subsystem is asymptotically stable and therefore will converge with time, then Agent2 will also converge to the delayed position information of Agent1.

The paper is structured as follows: Section II describes the principle and stability issues with time-delayed P-P architecture. Section III briefly discusses the gist of the Proxy-based approach to overcome the current shortcomings of position synchronisation and force transparency, followed by Section IV that provides detailed explanation and stability analysis. The experimental evaluations with static and active environments, time-varying delays, along with comparison with TDPA for P-P architecture are presented in Section V. Finally, Section VI concludes the work.

II. FUNDAMENTALS

Almost all teleoperated systems consist of multi-DoF arms. Hereon, for ease of understanding, the haptic input device and remote robot will be called main device (MD) and secondary device (SD). The dynamics of a n-DoF non-linear teleoperation system is given by:

$$M_i(x_i)\ddot{x}_i(t) + C_i(x_i, \dot{x}_i)\dot{x}_i(t) = f_{ic}(t) + f_i(t) \qquad (1)$$

where, i = 1,2 refers to MD and SD, $x_i \in R^n$ is the configuration, $M_i(x_i) \in R^{nxn}$ is the inertia matrix, $C_i(x_i, \dot{x}_i) \in R^{nxn}$ is the Coriolis matrix, $f_{ic}(t) \in R^n$ is the coupling controller acting on the main and secondary side, $f_i(t) \in R^n$ is the human operator's force on the MD or environment's force on the SD. Such a system possesses open-loop passivity due to (1) satisfying the following properties: (i) $M_i(x_i)$ is symmetric and positive definite, (ii) $\dot{M}_i - 2C_i$ is a skew-symmetric matrix.

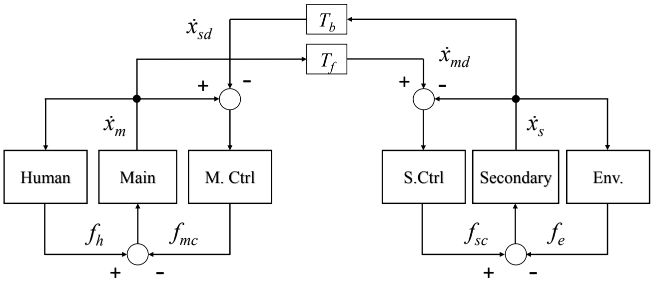
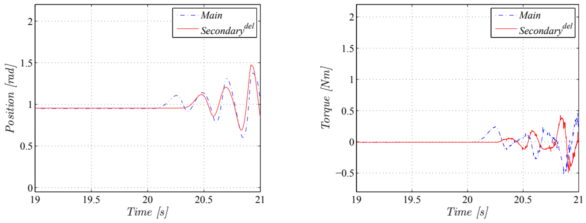


Fig. 1: Block diagram of a delayed bilateral P-P coupling architecture.



(a)

(b)

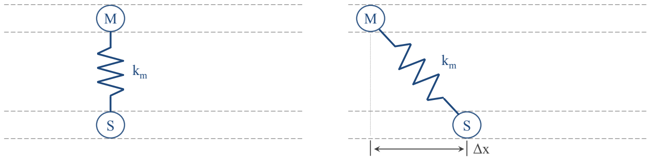
Fig. 2: No stabilizing controller results in an unstable interaction - T_{rt} = 200ms.

The control loop of the classical P-P architecture with human operator, MD, SD, and environment ($Env.$) is presented in Fig. 1. The positions of MD (x_m) and SD (x_s) are exchanged through the communication channel with unknown time-varying forward and backward delays T_f and $T_b \in R^+$. The two local controllers ($M.Ctrl$ on the main and $S.Ctrl$ on the secondary side) penalize a position deviation of main and secondary from the delayed secondary x_{sd} and main x_{md} position respectively. Generally, these controllers are implemented as spring-damper systems.

The delay in the communication channel has a severe destabilizing effect on the control loop. In terms of energy, this instability appears due to an energy generation by the delayed communication [23]. Such an effect can be seen in Fig. 2, where a main-secondary system is at equilibrium for a round-trip communication delay (T_{rt}) of 200ms. However, as soon as the human operator disturbs the system, energy starts flowing from main to secondary side and vice versa, and in the absence of stabilizing controllers, the teleoperator becomes unstable.

III. GIST OF THE PROPOSED BILATERAL CONTROL APPROACH

Let's consider two 1-DoF friction-less rails on which the MD and SD slides. They have a spring-damper (k_m, b_{mc}) coupling between them, however the damper is not shown to keep the figures uncluttered (Fig. 3a). The operator introduces energy into the system by moving the MD and releasing it, thus creating an offset between MD and SD, Δx, and (Fig. 3b). The system then begins to oscillate, with



(a) $\Delta x = 0$ (b) Δx

(c) $|\Delta x1| < |\Delta x|$ (d) $|\Delta x2| > |\Delta x|$

Fig. 3: Schematic explaining the gist of the proposed approach.

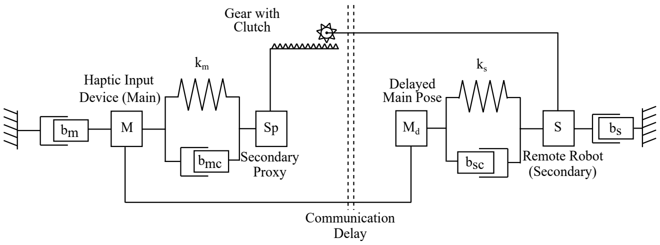


Fig. 4: Mechanical concept of the proposed Proxy-based approach.

each overshoot being less than the previous one ($|\Delta x_1| < |\Delta x|$) due to the introduced energy being dissipated by b_{mc} (Fig. 3c). Now when a communication delay is introduced to such a system, the overshoots increase rather than decrease ($|\Delta x_2| > |\Delta x|$) because the extra energy injected due to the delayed reference position information on both sides cannot be dissipated by b_{mc} (Fig. 3d).

In order not to inject energy due to the effect of delay, we propose to decouple MD and delayed secondary reference at the main side, in a sense that MD does not directly follow the delayed reference of SD, however the SD follows MD's delayed reference position (Fig. 4). A new local proxy position is introduced on the main side, which is the new reference for the MD. The position of the proxy is influenced by the delayed position of SD. Therefore, the SD has an indirect influence on MD through the proxy, whereas the MD has a direct influence on the SD. A controller which is implemented on the main side, is designed such that the proxy follows the delayed reference of SD only as long as it can ensure that the main-proxy subsystem is asymptotically stable. Assuming that the SD has a stable trajectory following controller, the SD will converge with respect to the MD's reference position, due to open-loop stability.

IV. PROPOSED PROXY-BASED APPROACH FOR BILATERAL TELEOPERATION CONTROL

Since the proposed approach is the initial theoretical work of a new control technique, the detailed analysis and experimental evaluation is presented for a 1-DoF system. Thus, the analysis of the proposed control approach would not be affected by nonlinearities and cross-coupling effects over the translational and rotational DoFs. Consider the bilateral teleoperator of Fig. 5, where the main and local proxy dynamics are given by:

$$m_m \ddot{x}_m(t) + b_m \dot{x}_m(t) + \alpha(t)\dot{x}_m(t) + k_m \tilde{e}_m(t) = 0 \quad (2)$$

where, $x_m(t)$ is the displacement, m_m is the mass, b_m is the viscous coefficient of the MD, $\alpha(t)$ is the local adaptive damping element on the main side, k_m is the discrete virtual spring coupling between MD and proxy, and $\tilde{e}_m(t) = x_m(t) - \tilde{x}_s(k)$ is the position error between the MD and proxy position ($\tilde{x}_s(k)$). Assuming that the MD's local servo rate is fast enough w.r.t. the update rate of $\tilde{x}_s(k)$, then the MD's controller ($k_m(x_m(t) - \tilde{x}_s(k))$) can be considered continuous [19]. k_m is parameterized in a passive way based on [20] which relates parameters of the controller, sampling frequency and the inherent physical damping of the device, thereby eliminating the effect of discretization and guaranteeing stability. Thus allowing us to define the switching control law in discrete time.

Three controllers and an observer that orchestrates switching between them, are introduced to stabilize the main-proxy subsystem. The switching is done such that the proxy mimics the delayed position of SD as accurately as possible without making the local main-proxy subsystem unstable:

$$\tilde{x}_s(k) = \begin{cases} Case(i): \\ \tilde{x}_s(k-1), \\ \qquad \text{for } \; |\tilde{e}_m(k)| < |e_m(k)| \\ \qquad \&\& \; |\tilde{e}_m(k)| > |\tilde{e}_m(k-1)| \\ Case(ii): \\ \tilde{x}_s(k-1) + x_m(k) - x_m(k-1), \\ \qquad \text{for } \; |\tilde{e}_m(k)| < |e_m(k)| \\ \qquad \&\& \; |\tilde{e}_m(k)| \leq |\tilde{e}_m(k-1)| \\ Case(iii): \\ x_s(k - T_b), \\ \qquad \text{for } \; |\tilde{e}_m(k)| \geq |e_m(k)| \end{cases} \quad (3)$$

where, $e_m(k) = x_m(k) - x_s(k - T_b)$ is the position error between the current position of MD and SD position delayed by T_b.

Case(i):

The observer detects if the human operator is injecting energy into the main-proxy subsystem by extending the coupling spring, k_m, through moving the MD, $|\tilde{e}_m(k)| > |\tilde{e}_m(k-1)|$ (Fig. 6a). It also detects if the delayed secondary position is trying to inject energy alongside MD, $|\tilde{e}_m(k)| < |e_m(k)|$. In either case, the controller holds the proxy position to its previous position, $|\tilde{x}_s(k)| = |\tilde{x}_s(k-1)|$. This means that the potential energy bounds of the coupling spring will be increased, if at all, only by the operator through moving the MD.

Case(ii):

The observer detects whether or not there is an offset between the delayed secondary position and the proxy position, $|\tilde{e}_m(k)| < |e_m(k)|$, while the MD is holding its previous position or is moving towards the delayed secondary

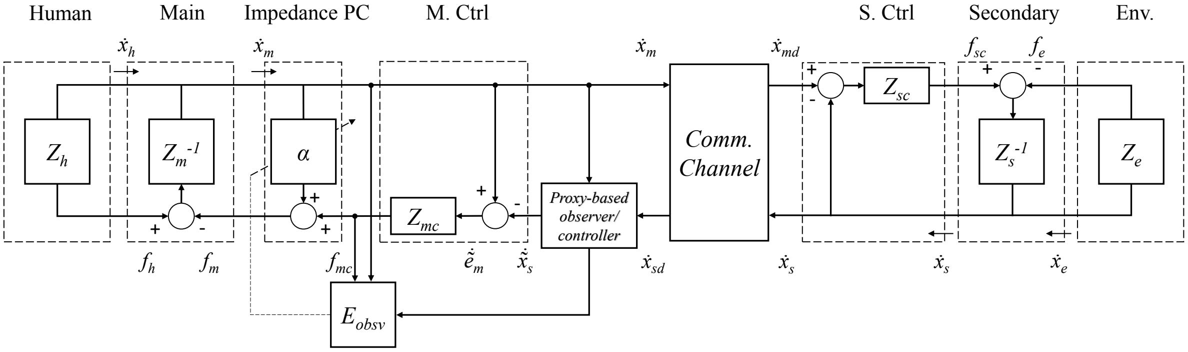
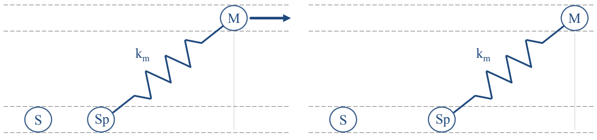
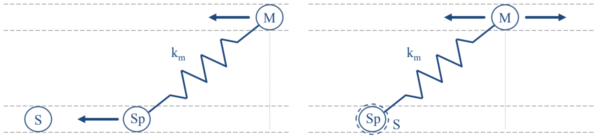


Fig. 5: Block diagram of a delayed P-P teleoperation system with the proposed Proxy-based control approach.



(a) Case(i) (b) Case(ii)



(c) Case(ii) (d) Case(iii)

Fig. 6: Schematic explaining the switching instances of the proposed controller based on the state of the main-proxy subsystem. M, S, and S_p denote the main, secondary, and proxy.

position, $|\tilde{e}_m(k)| \leq |\tilde{e}_m(k-1)|$ (Figs. 6b, 6c). This triggers the controller which shifts the proxy position by the same magnitude and in the same direction as the MD. In other words, this introduces a saturated spring between the MD and proxy (Fig. 6c). This would add a saturated force onto the MD, in the direction of the SD, until the proxy position reaches the delayed secondary position, $|\tilde{e}_m(k)| = |e_m(k)|$.

Case(iii):

The observer detects if $|\tilde{e}_m(k)| \geq |e_m(k)|$. If true, the controller sets the proxy position equal to the delayed secondary position ($|\tilde{x}_s(k)| = |x_s(k-T_b)|$), which makes $|\tilde{e}_m(k)| = |e_m(k)|$. In this state $|\tilde{x}_s(k)|$ will either hold its previous position or move towards the MD's current position (Fig. 6d).

Proposition 1: The main-proxy subsystem described by (2), is asymptotically stable using the switching control laws described in (3).

Proof: Consider the Lyapunov function candidate as the total energy of the main-proxy subsystem:

$$V(t) = \frac{1}{2} m_m \dot{x}_m(t)^2 + \frac{1}{2} k_m \tilde{e}_m(t)^2 \tag{4}$$

The derivative of $V(t)$ with respect to time is:

$$\dot{V}(t) = m_m \dot{x}_m(t) \ddot{x}_m(t) + k_m \tilde{e}_m(t) \dot{\tilde{e}}_m(t) \tag{5}$$

Substituting $m_m \ddot{x}_m(t)$ from (2) to (5):

$$\begin{aligned} \dot{V}(t) &= -b_m \dot{x}_m(t)^2 - \alpha(t) \dot{x}_m(t)^2 - k_m \tilde{e}_m(t) \dot{x}_m(t) \\ &\quad + k_m \tilde{e}_m(t) \dot{\tilde{e}}_m(t) \\ &= -b_m \dot{x}_m(t)^2 - \alpha(t) \dot{x}_m(t)^2 - k_m \tilde{e}_m(t) \dot{x}_m(t) \\ &\quad + k_m \tilde{e}_m(t) (\dot{x}_m(t) - \dot{\tilde{x}}_s(k)) \\ &= -b_m \dot{x}_m(t)^2 - \alpha(t) \dot{x}_m(t)^2 - k_m \tilde{e}_m(t) \dot{\tilde{x}}_s(k) \end{aligned} \tag{6}$$

The above equation can also be represented in terms of its Zero Order Hold component, $\dot{V}_{ZOH}(t)$:

$$\dot{V}(t) = \dot{V}_{ZOH}(t) + \epsilon_r(t) \tag{7}$$

where, $\epsilon_r(t)$ is the residual term. If k_m is parameterized according to [20], then $\epsilon_r(t)$ should not influence on stability. Therefore, the discrete time version of $\dot{V}(t)$, i.e. $\dot{V}(k)$, is used hereon for the remainder of the proof, on the condition that k_m is chosen to be below a certain threshold value which is defined by [20].

$$\dot{V}(k) = -b_m \dot{x}_m(k)^2 - \alpha(k) \dot{x}_m(k)^2 - k_m \tilde{e}_m(k) \dot{\tilde{x}}_s(k) \tag{8}$$

Case (i):

From the first switching condition described in (3), when $|\tilde{e}_m(k)| < |e_m(k)| \&\& |\tilde{e}_m(k)| > |\tilde{e}_m(k-1)|$, then $\tilde{x}_s(k) = \tilde{x}_s(k-1)$, therefore, $\dot{\tilde{x}}_s(k) = 0$. Also $\alpha(k)$ is set to 0 in this case. Thus, $\dot{V}(k)$ in (8) will be negative definite.

Case (ii):

In this switching controller, the coupling spring (k_m) is saturated which will exert a constant force on the MD. This constant force would monotonously increase the kinetic energy of MD, and the main-proxy subsystem won't be asymptotically stable anymore because of this injection of energy. Due to the action of the saturated spring, $e_m(k) > 0$ would result in $\dot{\tilde{x}}_s(k) < 0$ whereas $e_m(k) < 0$ would mean that $\dot{\tilde{x}}_s(k) > 0$. Thus, this will not result in $\dot{V}(k)$ to be negative definite.

The introduction of saturated spring is necessary for the MD's position to reach the proxy position, which in turn is following the delayed secondary position. Therefore, TDPA is used as a tool to monitor via Passivity Observer (PO), and dissipate via Passivity Controller (PC), the extra energy that is being added to the main-proxy subsystem due to the saturated spring. The main-proxy subsystem can be considered analogous to a one-port system, where PO may or may not be negative at a particular time, depending on the operating conditions and the specifics of the one-port element's dynamics. Assuming zero initial energy storage, the power conjugate variables $f_{mc}(k)$ and $\dot{x}_m(k)$ are used to monitor the energy flow:

$$\begin{aligned} E_{obsv}(k) = E_{obsv}(k-1) + [f_{mc}(k)\dot{x}_m(k) + \\ \alpha(k-1)\dot{x}_m(k-1)^2]T_s \end{aligned} \tag{9}$$

where $f_{mc}(k)$ is the force output of the main controller, and T_s is the sampling time. If $E_{obsv}(k) \geq 0$ for every k, then this means that the one-port is dissipative. If at any instance $E_{obsv}(k) < 0$, then the one-port generates energy and the amount of generated energy is $-E_{obsv}(k)$, which may contribute towards instability. The PC takes the form of a time-varying element ($\alpha(k)$) in a series configuration with impedance causality, to dissipate only the required amount of energy [4].

$$\alpha(k) = \begin{cases} -\frac{E_{obsv}(k)}{T_s \dot{x}_m(k)^2}, & \text{if } E_{obsv}(k) < 0 \\ 0, & \text{if } E_{obsv}(k) \geq 0 \end{cases} \tag{10}$$

Therefore, the TDPA assures that no extra energy gets injected into the main-proxy subsystem due to the action of the saturated spring. Substituting α from (10) to (8):

$$\begin{aligned} \dot{V}(k) &= -b_m\dot{x}_m(k)^2 - \alpha(k)\dot{x}_m(k)^2 - k_m\tilde{e}_m(k)\dot{\tilde{x}}_s(k) \\ &= -b_m\dot{x}_m(k)^2 + \frac{E_{obsv}(k)}{T_s} - k_m\tilde{e}_m(k)\dot{\tilde{x}}_s(k) \end{aligned}$$

Substituting $E_{obsv}(k)$ from (9):

$$\begin{aligned} &\dot{V}(k) = -b_m\dot{x}_m(k)^2 + \\ &\frac{E_{obsv}(k-1) + [f_{mc}(k)\dot{x}_m(k) + \alpha(k-1)\dot{x}_m(k-1)^2]T_s}{T_s} \\ &- k_m\tilde{e}_m(k)\dot{\tilde{x}}_s(k) \end{aligned}$$

Replacing $f_{mc}(k) = k_m\tilde{e}_m(k)$:

$$\begin{aligned} &\dot{V}(k) = -b_m\dot{x}_m(k)^2 + \\ &\frac{E_{obsv}(k-1) + [k_m\tilde{e}_m(k)\dot{x}_m(k) + \alpha(k-1)\dot{x}_m(k-1)^2]T_s}{T_s} \\ &- k_m\tilde{e}_m(k)\dot{\tilde{x}}_s(k) \\ &= -b_m\dot{x}_m(k)^2 + \\ &\frac{E_{obsv}(k-1) + [\alpha(k-1)\dot{x}_m(k-1)^2]T_s}{T_s} \\ &+ \frac{[k_m\tilde{e}_m(k)\dot{x}_m(k)]T_s}{T_s} - k_m\tilde{e}_m(k)\dot{\tilde{x}}_s(k) \\ &= -b_m\dot{x}_m(k)^2 + \\ &\frac{E_{obsv}(k-1) + [\alpha(k-1)\dot{x}_m(k-1)^2]T_s}{T_s} \\ &+ k_m\tilde{e}_m(k)(\dot{x}_m(k) - \dot{\tilde{x}}_s(k)) \end{aligned}$$

In Case (ii): $E_{obsv}(k-1) + [\alpha(k-1)\dot{x}_m(k-1)^2]T_s = 0$, and $\dot{x}_m(k) = \dot{\tilde{x}}_s(k)$.

$$\dot{V}(k) = -b_m\dot{x}_m(k)^2 \tag{11}$$

Thus, the addition of an adaptive dissipative element in series guarantees that the main-proxy subsystem is asymptotically stable, as $\dot{V}(k)$ is always negative definite.

Please note that $E_{obsv}(k)$ is only computed in case(ii). In case(i) and (ii) $E_{obsv}(k)$ is set to 0 which also makes $\alpha(k) = 0$

Case (iii):

The third switching condition will be triggered when $|\tilde{e}_m(k)| \geq |e_m(k)|$, which will make $\tilde{x}_s(k) = x_s(k - T_b)$. $\alpha(k)$ is set to 0 in this case.

Therefore, when $e_m(k) > 0$, then for $|x_m(k) - \tilde{x}_s(k)| \geq |x_m(k) - x_s(k - T_b)|$ to be true, $x_s(k - T_b) \geq \tilde{x}_s(k)$, thereby making $\dot{\tilde{x}}_s(k) \geq 0$. Thus, $\dot{V}(k)$ in (8) will always be negative definite.

And when $e_m(k) < 0$, then for $|x_m(k) - \tilde{x}_s(k)| \geq |x_m(k) - x_s(k - T_b)|$ to be true, $x_s(k - T_b) \leq \tilde{x}_s(k)$, thereby making $\dot{\tilde{x}}_s(k) \leq 0$. Thus, $\dot{V}(k)$ in (8) will always also be negative definite.

Also $e_m(k) = 0$ in (8) will result in $\dot{V}(k)$ to be negative definite.

The proposed Proxy-based controller uses a common Lyapunov function to prove that the main-proxy subsystem is asymptotically stable for all the three switching instances. The secondary controller, using a stable trajectory following controller, follows the delayed main reference, and therefore the main, proxy and secondary positions converge. The human operator, while interacting with the MD, injects energy into the main-proxy coupling. However, when the operator releases the MD, the proposed controller decreases the energy monotonously due to dissipation by the inherent physical damping of the MD and the adaptive damping element of the PC.

V. EXPERIMENTAL EVALUATION

A. Experimental Setup

Figure 7 shows two 1-DoF rotational devices used as the teleoperation setup. Both have a sampling rate of 1 kHz. A P-P control architecture with coupling gain of k_m = 1.5 N/mm, b_{mc} = 0.01 Ns/mm on the main side and, k_s = 1.5 N/mm, b_{sc} = 0.01 Ns/mm on the secondary side was implemented. The gains were tuned such that at no-delay the energy generated by discretization was dissipated and therefore the teleoperator was passive.

B. Experimental Results for Proxy-based Controller

The experiments for the proposed controller were carried out with the operator maneuvering the MD to make contact with a hard wall (over 150 N/mm), located at 0.85 rad, via the SD. Even for a well-tuned coupling controller, such an interaction would become unstable upon the introduction of "large" time-delay. This can be seen from Fig. 2, where the system becomes unstable when the operator disturbs the MD and releases it, for a round-trip delay of 200ms.

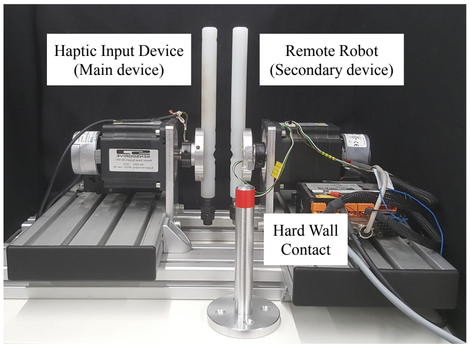
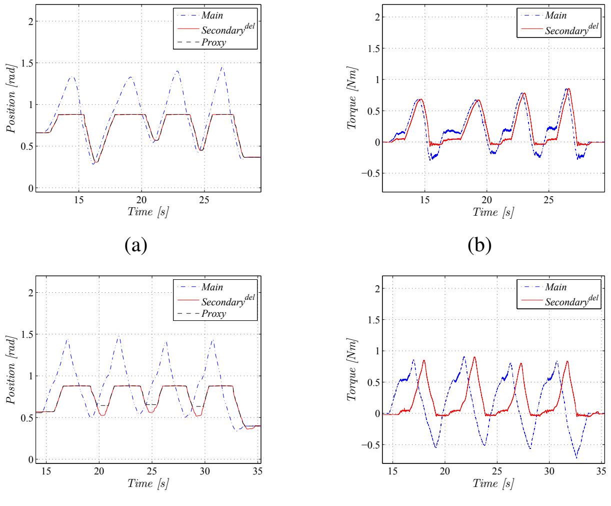


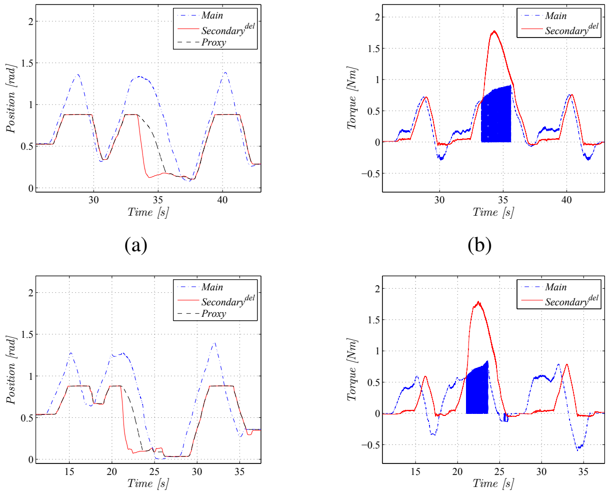
Fig. 7: Experimental setup: Two 1-DoF rotational devices with a hard wall contact.



(a) (b)

(c) (d)

Fig. 8: Proposed Proxy-based controller has no position drift and displays transparent torque information for T_{rt}=200ms[(a), (b)] and 1000ms[(c), (d)].



(a) (b)

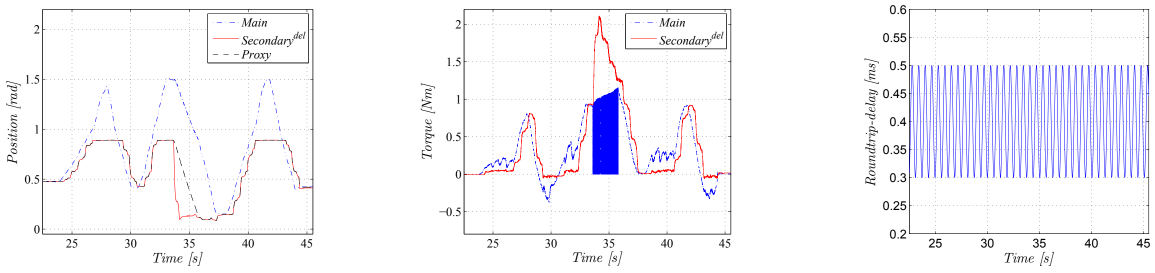
(c) (d)

Fig. 9: Proposed Proxy-based controller maintains stability with an active environment for T_{rt} = 200ms [(a), (b)] and 1000ms [(c), (d)].

1) Static environment with constant time delay: The same experiment was repeated by implementing the proposed controller, where the operator made 4 contacts with a static environment, Fig. 8. For T_{rt} = 200ms, the delayed secondary position and proxy position are almost identical and there is no position drift present between the MD and SD. Figure 8b shows that the MD and SD exhibit similar torque values when the user makes contact with the environment. Even for higher delays of T_{rt} = 1000ms, the interaction stays stable, but the proxy position does not accurately follow the delayed secondary position, as seen in Fig. 8c. There are some instances where the proxy holds its previous position while ignoring the delayed secondary reference (t = 20-22s, 24-25.5s, 28.5-30s). However, the position drift between the MD and SD is absent and the generated main and secondary torques are almost identical when the operator makes contact with the environment. This goes on to show that the impedance-type PC doesn't trigger when the operator is interacting with a static environment, thereby enhancing the transparency.

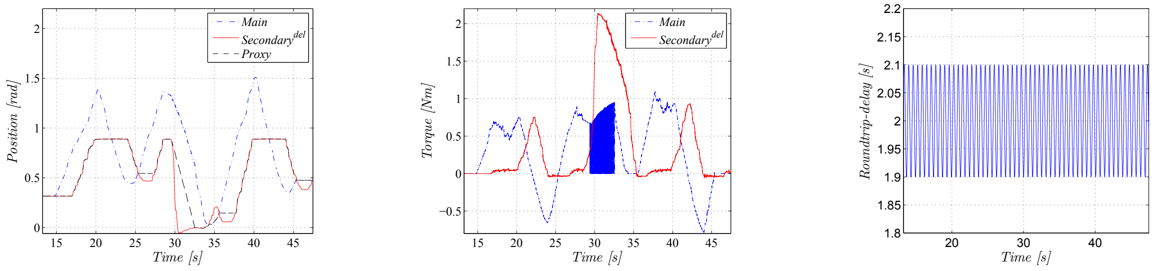
2) Active environment with constant time delay: For the next set of experiments, the operator made three contacts with the environment. The environment was static during the first and last interaction, but active during the second interaction. It can be observed from Fig. 9 that during the first and last contact, for T_{rt} = 200ms and 1000ms, the delayed secondary and proxy position are almost identical and the torque information is symmetrical, which is analogous to experiments conducted in Fig. 8. However, during the second contact, when the environment with which the SD was in contact, was made active (t=33.5-34.5s in Fig. 9a, and t=22-23s in Fig. 9c), high frequency torque oscillation is observed at the main side (Figs. 9b and 9d) because of the triggering of impedance-type PC due to extra energy being injected into the main-proxy subsystem. This extra energy is generated due to the saturated discrete coupling spring as explained in Section IV, and which is dissipated by the adaptive damping element of PC. Once the proxy reaches the delayed secondary reference (t=36s in Fig. 9a, and t=24s in Fig. 9c), the PC is no longer triggered and therefore the torque oscillation stops. This high frequency oscillations is very typical of impedance-type PC and can be removed using a virtual mass spring (VMS) passive filter [4].

3) Active environment with time-varying delay: Figures 10 and 11 show the results for experiments conducted with time-varying delays of 400±100ms (Fig. 10c) and 2000±100ms (Fig. 11c). It can be seen that time-varying delay does not have an effect on the stability of the system. Similar to the previous experiments as seen in Fig. 9, the PC starts dissipating the generated energy only when the environment becomes active (t=34-34.5s in Fig. 10a, and t=22-23s in Fig. 11a). During the first and last interaction with the environment, the PC was not triggered and thus the torque profile did not exhibit any high frequency oscillations.



(a) (b) (c)

Fig. 10: Proposed Proxy-based controller maintains stability with an active environment for time-varying delay of 400±100ms (a) Position, (b) Torque, (c) Time-varying round-trip delay.



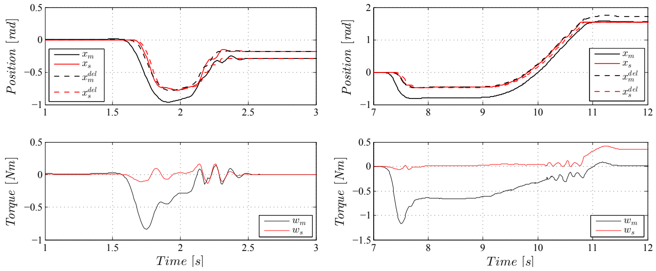
(a) (b) (c)

Fig. 11: Proposed Proxy-based controller maintains stability with an active environment for time-varying delay of 2000±100ms (a) Position, (b) Torque, (c) Time-varying round-trip delay.

C. TDPA for P-P Teleoperation Architecture

For comparison analysis, this section provides experimental results of TDPA proposed for P-P architecture [23], where the PCs act with a variable damping on the velocity signals (admittance type PCs) that exit the TDPNs in direction to the coupling controllers.The major drawback of admittance type PCs is a position drift that appears after the integration of a varied velocity signal. Drift compensation methods cannot compensate the drift instantaneously but only when the energy in the system and thus the physical coupling situation allows. Especially in P-P architectures critical coupling configurations can appear due to position drift.

In the teleoperation experiment (compare Fig. 7) at $T_{rt} = 30ms$ round-trip delay presented in Fig. 12a, the MD commands a motion of the SD. At $t = 2.5s$, a position drift is visible since the secondary reference position (x_{md}) does not match with the MD position (x_m) and the main reference position (x_{sd}) does not match with the SD position (x_s). Occasionally, the drift equals for both PCs such that the coupling controllers find a suitable configuration. In contrast, the experiment displayed in Fig. 12b ($T_{rt} = 100ms$), the drift in x_{sd} is higher than the drift in x_{md}. Therefore, at $t = 8.5s$, the MD has to act against a torque which results from $M.Ctrl$ that penalizes the deviation of x_{sd} and x_m. In contrast, the error between x_s and x_{md} could be reduced by $S.Ctrl$. When the human operator stops acting against this torque ($t = 9s$), the MD is pushed back until the SD reaches a wall at $t = 10.8s$. Then, $S.Ctrl$ tries to reduce the respective position error whereas $M.Ctrl$ is confident. Thus, the TDPA leads to weak performance and disturbed feedback.



(a) (b)

Fig. 12: PP-architecture of [23]: position drift at slow motion for (a) T_{rt} = 30ms, and (b) T_{rt} = 100ms.

Comparing Figs. 8, 9, 10, and 11 with Figs. 12a, 12b, it can be observed that the proposed approach delivers better results and completely eliminates position drift, even for delays of up to $2s$. The torque profile is also more smooth, and the main and secondary controllers are synchronized in contrast to TDPA.

VI. CONCLUSION AND FUTURE WORK

The control approach presented in this paper enhances the position synchronization of agents suffering from delayed coupling while maintaining stability, by introducing a local proxy reference to one of the agents and only closing the feedback loop when it can preserve stability. One of the advantages of the proposed Proxy-based controller is that it is only implemented on the main side, in-between the communication channel and $M.Ctrl$, whereas the SD can continue to use only a tracking controller. Also no prior information of system parameters is required, as the observer orchestrates switching between different controllers based on the state of the agent-proxy subsystem. It presents clear advantages over TDPA for P-P architecture, by completely removing position drift without sacrificing force transparency even for delays of $2s$, thereby transmitting more realistic feedback to the operator. The proposed controller can also ensure stability for active environments, although high frequency oscillations of impedance-type PC are present, but these can be filtered out using a VMS passive filer. To the best of the authors' knowledge no other time-delayed control approach for P-P architecture can eliminate position drift without sacrificing transparency, for such high time-delays.

Future work will include extension from 1-DoF to 6-DoF and implementing a VMS to filter out the high frequency force oscillations, mostly experienced during active contacts, and test its robustness to packet loss annd jittering. The proposed approach will be compared with [3], [19], [29], and also research will be directed towards incorporating them instead of TDPA for dealing with the effects of saturated spring.

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