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Perceptual-based Method for Mitigating Force Chattering in Time Domain Passivity Approach

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***Abstract*—Time-delay in bilateral teleoperation systems often leads to passivity violations, necessitating the use of stability controllers. Time domain passivity approach has garnered attention within the haptics and tele-robotics field, due to demonstrating significant robustness while being less conservative compared to other passivity-based approaches. However, it's affected by two types of artifacts, namely position drift and high-frequency force vibration. This paper presents a perceptual-based scaling method to mitigate such vibrations, which would otherwise adversely affect transparency and user perception. The proposed method uses Weber's law to leverage human haptic perception thresholds to scale the delayed feedback force during the energy-out phase on the human operator side. By selectively scaling the feedback force within the human just-noticeable difference (JND) threshold, the activation of impedance-type passivity controller is reduced while maintaining overall system passivity. Experimental validation using a 1-DoF teleoperation system with 200 ms and 500 ms round-trip delay, demonstrates a significant reduction in high-frequency force vibrations.**

***Index Terms*—Time Domain Passivity Approach, Perceptual-based method, force chattering, bilateral teleoperation.**

I. Introduction

Teleoperation is utilized across various fields of application, for instance robotic minimally invasive surgery [1], telenavigation [2], hazardous environment handling [3], space [4], [5], military [6], underwater exploration [7], industry [8], and search and rescue operations [9]. There are several key challenges in teleoperation, such as time-delay, stability and control issues, lack of force feedback, bandwidth constraints, human operator fatigue, and limited situational awareness. Among these, stability issues induced by time-delays, arising due to the remote positioning of the robotic system, are particularly significant as they directly impact efficiency, safety, and user experience. In delayed systems, the commanded and feedback signals transmitted over the communication channel suffers from an intrinsic time-delay, which, even at small magnitudes, can have severe destabilizing effects [10].

Ensuring stability in teleoperation is a nontrivial task. Over the years, extensive research has been conducted to mitigate the adverse effects of time delay. Among the various approaches, passivity-based method, such as wave variables [11], energy tanks [12], and the Time Domain Passivity Approach (TDPA) [13], [14] have demonstrated significant robustness. These methods are particularly advantageous due to their broad applicability to both linear and nonlinear systems, their ability to provide a sufficient condition for stability, and their reliance solely on input-output information, independent of system parameters. TDPA has been successful in addressing various control challenges in robotics, such as non-collocated force sensing [15], authority scaling [16], [17] or delayed coupling [18], [19]. However, despite its advantage, TDPA-controlled delayed teleoperation systems are affected by two types of artifacts: drift in position command and jitter or high-frequency chattering in force feedback. Position drift occurs due to the adaptive damping dissipating excessive energy on the robot side, while force chattering result from the passivity control action varying the force on the operator side of the communication channel. Researchers have tackled position drift through various approaches, including position-drift compensation methods [20], [21] , novel TDPA architectures as the energy-reflection based TDPA (TDPA-ER) [22], and using proxy-based method [23].

Relatively, less research has been focused on the reduction the force chattering. A passive filter based on a virtual mass-spring (VMS) damper system was introduced in [14]. However, this method has drawbacks such as increased tuning efforts, hardware dependency, and the introduction of an additional mass in the coupling, causing phase shifts that limit force transparency. In the chattering-free approach, a nonzero velocity threshold is employed in place of the conventional zero-velocity threshold typically used in TDPA with and without VMS [24]. By operating within this threshold, the adaptive damping of the passivity controller is scaled down, effectively mitigating force jittering behavior at low velocities. However, the velocity threshold is a function of the delay, therefore, higher time-delays will minimize its effectiveness. Although, the observer-based gradient method (OBG) [25] was developed focusing on maintaining a physically reasonable force feedback information in delayed systems, it also reduced the chattering caused by impedance-type passivity controllers partially. This effect arose from the intended downscaling of the force feedback by the OBG acting as a dissipative element, thus taking over parts of the passivity controller's task. Inspired by this effect, in this work, we formulate a method for force feedback scaling on the operator side that tackles the chattering with a clear physical reasoning by

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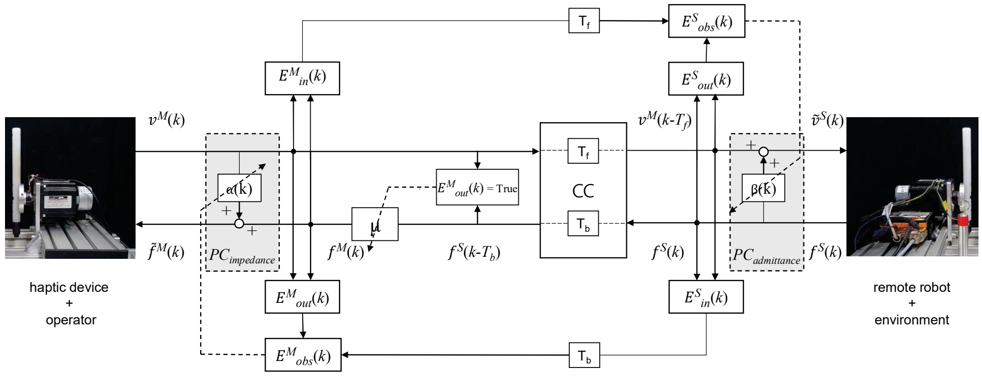


Fig. 1. Block diagram of the proposed perceptual-based method to reduce the high-frequency force chattering of impedance type passivity controller.

considering the energy-flow direction. The scaling down of delayed feedback force, based on the energy-flow direction, reduces the activation frequency of passivity controller, thus reducing force discontinuities. Since, indiscriminate force scaling could degrade the operator's haptic experience, the perceptual threshold is used as scaling to preserve the perceived fidelity of the haptic feedback. The proposed perceptual-based scaling method reduces the chattering of the impedance-type passivity controller, is not dependent on the communication delay, is only implemented on the operator side, and does not require additional signals transmitted or computations on the remote robot side.

The manuscript is organized as follows: Section II reviews the TDPA, the proposed method is introduced in Section III, and its experimental evaluation for teleoperation with delayed communication is shown in Section IV. The work is concluded in Section V.

II. Review of the Time Domain Passivity Approach

Ensuring the passivity of a teleoperation two-port network is a sufficient condition to achieve stable bilateral teleoperation [26]. It is well-established that the overall passivity of a teleoperation system can be guaranteed if each of its constituent subsystems is passive, i.e., the haptic device, remote robot, communication channel, human operator, and environment. The haptic device and remote robot are inherently passive. Although human operator and the robot's environment may exhibit active behavior, it is generally assumed that they behave passive during interaction. This is confirmed by the observation that humans are used to use passive tools in active environments. However, the activity of the communication channel is dependent on the delay and requires the action of a controller to passivate it.

The TDPA is a control strategy used in teleoperation systems to ensure stable interaction between the haptic device and the remote robot, even in the presence of delay or uncertainities. It ensures passivity of the active communication channel, by monitoring the energy exchanges on either side of the CC using a Passivity Observer (PO) and dissipating excess energy through a Passivity Controller (PC) to maintain the passivity of the channel.

A sufficient condition to satisfy the passivity requirement, particularly under conditions of communication delays, is given by:

$$E^M_{obs}(k) = E^S_{in}(k - T_b) - E^M_{out}(k) \geq 0, \forall k \geq 0, \quad (1)$$

$$E^S_{obs}(k) = E^M_{in}(k - T_f) - E^S_{out}(k) \geq 0, \forall k \geq 0, \quad (2)$$

where, $E^M_{obs}(k)$ and $E^S_{obs}(k)$ denote the observed secondary to main and main to secondary energy flows on the respective sides of the CC. $E^M_{in}(k - T_f)$, $E^M_{out}(k)$, $E^S_{in}(k - T_b)$, and $E^S_{out}(k)$ are non-negative, monotonically increasing functions. T_f and T_b are the forward and backward communication delays. Both conditions are sufficient to ensure passivity of the delayed teleoperation system [26].

Passivity Observer: The real-time assessment of the observed passivity conditions, as specified in (1) and (2), is carried out by the POs, which monitor the energies W^M and W^S on the main and secondary sides. The POs' calculations also consider the energy dissipation previously executed by the respective PCs:

$$W^M(k) = E^S_{in}(k - T_b) - E^M_{out}(k) + E^M_{PC}(k - 1), \quad (3)$$

$$W^S(k) = E^M_{in}(k - T_f) - E^S_{out}(k) + E^S_{PC}(k - 1), \quad (4)$$

where, $E^M_{PC}(k-1)$ and $E^S_{PC}(k-1)$ are the energies dissipated by the main and secondary PCs up to the previous time step.

Passivity Controller: The passivity controllers are adaptive energy-dissipating elements that dissipate any excess energy identified by the POs. As depicted in Fig. 1, the PC is applied in both impedance (main side) and admittance (secondary side) configurations within a Position-Force computed (P-Fc) architecture.

$$\alpha(k) = \begin{cases} \frac{W^M(k)}{\Delta T (v^M(k))^2}, & \text{if } W^M(k) < 0 \text{ and } v^M(k) \neq 0 \\ 0 & \text{else} \end{cases} \quad (5)$$

$$\beta(k) = \begin{cases} \frac{W^S(k)}{\Delta T (f^S(k))^2}, & \text{if } W^S(k) < 0 \text{ and } f^S(k) \neq 0 \\ 0 & \text{else} \end{cases} \quad (6)$$

where, α and β are adaptive damping elements that dissipate the extra generated energy, thereby guaranteeing the passivity conditions presented in (1) and (2). The impedance-type passivity controller (PC_{imp}) modifies the delayed feedback force to the main side and the admittance-type passivity controller (PC_{adm}) modifies the delayed main's reference velocity to the secondary side.

$$\tilde{f}^M(k) = f^S(k - T_b) + \alpha(k)v^M(k) \tag{7}$$

$$\tilde{v}^S(k) = \dot{x}^S(k) + \beta(k)f^S(k) \tag{8}$$

where, $\tilde{f}^M(k)$ is the modified force to the main device, and $\tilde{v^S}(k)$ is the adjusted velocity reference to the secondary device.

III. Proposed Perceptual-based Method

This section highlights the limitation of TDPA and presents a perceptual-based method to mitigate it in a straightforward manner. The proposed method is implemented exclusively on the main side, eliminating the need for additional signal transfers or computations on the secondary side.

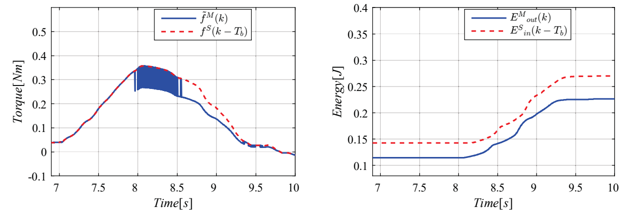
A. Artifacts of TDPA

There are two shortcomings of the TDPA, high-frequency force chattering persistent on the main side due to action of PC_{imp} and position drift on the secondary side due to the action of admittance-type PC. This paper will focus on the prior, propose a solution that is simple to implement and can reduce the high-frequency force chattering.

The PC_{imp} configuration induces a high-frequency discontinuous force modification (chattering behavior) during relatively low velocity operations. This phenomenon arises from the triggering of the PC_{imp} that can distort the force information and produce discomfort for the human operator, potentially leading to system instability by exciting the natural frequencies of the teleoperation dynamics [27]. The primary cause of chattering in a conventional TDPA system is attributed to noisy velocity measurements during low-velocity interactions. The adaptive damping α for the PC_{imp} is highly sensitive to velocity noise, as it is derived by numerically dividing the observed energy by the square of the velocity, as defined in (5). When the velocity approaches zero, the noise is amplified, leading to substantial force modifications. Additionally, zero velocity, exacerbated by sensor quantization, induces a pronounced on/off force effect [28].

B. Proposed solution to reduce high-frequency force chattering

During contact with the environment in a delayed teleoperation system, the activation of the PC_{imp} is contingent on the human operator's interaction dynamics, specifically when pulling back from contact with the remote environment. Ideally, the velocity of the haptic device $v^M(k)$ changes direction when the human operator is intending to make or break contact with the environment. This change of direction facilitates energy transfer from the secondary side to the main side, which may trigger the PC_{imp} (5) if (3) is violated.



(a) (b)

Fig. 2. (a) Effect of selective scaling on delayed feedback force during high frequency switching between energy-in and energy-out phases, seen during $t \approx 7.950$ - 8.550 s; (b) Passivity-gap introduction due to the effect of selective scaling.

When the haptic device is pushing the remote robot into the environment, the energy-in $E^M_{in}(k)$ on the main side monotonically increases, while the energy-out $E^M_{out}(k)$ remains constant. As a result, the PC_{imp} remains inactive since the net energy balance $W^M(k) \geq 0$. However, during retraction, when the operator pulls the remote robot out of contact with the environment, the energy-out $E^M_{out}(k)$ begins to monotonically increase, while the energy-in $E^M_{in}(k)$ remains constant. Under these conditions, the PC_{imp} may activate if $W^M(k) < 0$, preventing energy build-up that could destabilize the system.

Down-scaling the delayed feedback force in TDPA on the main side does not violate the passivity of P-Fc bilateral teleoperation system, if the dissipation happens in an energy-flow direction dependent manner [29]. However, it does not inherently enhance haptic performance in terms of reducing the force chattering. But, if $E^M_{out}(k)$ in (3) is reduced, the frequency of PC_{imp} activation would potentially decrease, thus smoothing the interaction and reducing force discontinuities. The method proposed in this paper to achieve reduced force discontinuities is to scale down $f^S(k - T_b)$ when energy flows out of the CC on the main side, i.e., when $f^S(k - T_b) \cdot v^M(k) < 0$. However, indiscriminate force reduction could degrade the operator's haptic perception by introducing abrupt force changes, thereby discarding the advantage that the proposed method may have over TDPA. This trade-off between reducing PC-induced chattering and maintaining haptic fidelity depends on various factors such as application or task at hand, capabilities of the haptic device, and the operator's subjective perception.

Human haptic perception is inherently constrained, a limitation well-characterized by Weber's law, which models the perceptual sensitivity to changes in stimulus intensity [30]. According to this law, the smallest detectable difference (ΔI) in intensity between two stimuli, known as the just noticeable difference (JND), is proportional to the initial intensity (I) of a reference stimulus, expressed as $\Delta I/I = \epsilon$, where ϵ is the Weber Fraction (WF). The JND, determined through psychophysical experimentation, represents the threshold at which a change in stimulus becomes perceptible. For haptic feedback, the WF varies depending on the nature of the stimulus, whether it be force or velocity, and the specific limb or joint to which the stimulus is applied [31]. Leveraging this principle in the context of passivity of time-delayed teleoperation, scaling the delayed feedback force $f^S(k-T_b)$ based on the operator's perceptual threshold (i.e., the WF) can result in fewer activations of the PC_{imp} without the operator detecting a significant change in haptic feedback. This is because the scaled force remains within the operator's JND, effectively reducing unnecessary PC activations while preserving the perceived fidelity of the interaction.

To integrate this perceptual-based force scaling into the TDPA framework, the $E^M_{out}(k)$ on the main side is observed. When energy outflow is detected, i.e., monotonous increase in $E^M_{out}(k)$, the delayed force $f^S(k-T_b)$ is scaled down by a factor μ, ($f^M(k) = \mu f^S(k-T_b)$), as depicted in the block diagram in Fig. 1. This scaled force is then used to compute the updated PO, which then triggers the PC_{imp} to further modify $f^M(k)$ if passivity is violated. As illustrated in Fig. 2(a), this concept is demonstrated through a force vs. time plot. Here an ϵ = 20% was selected [32]. During $t \approx$ 7.950 - 8.550 s the PO keeps switching between $E^M_{out}(k)$ and $E^M_{in}(k)$ phases. During the $E^M_{out}(k)$ phase, the delayed feedback force $f^S(k-T_b)$ is scaled by μ, while it's not scaled during $E^M_{in}(k)$ phase. This switching causes force vibrations. However, the amplitude of these vibrations is relatively smaller compared to conventional TDPA, and are hardly noticeable by the human operator since the scaling factor is based on the perceptual threshold. The comparison between TDPA and proposed method is presented in Section IV. Algorithm 1 presents the proposed method incorporating the WF to enable reduction in high-frequency force chattering. The perceptual-based method could create

Algorithm 1: perceptual-based method

if $f^S(k-T_b).v^M(k) \geq 0$ **then**
  $E^M_{in}(k) = E^M_{in}(k-1) + f^S(k-T_b).v^M(k)$
  $E^M_{out}(k) = E^M_{out}(k-1)$
else
  $\mu = 1 - \epsilon$
  $f^M(k) = f^S(k-T_b).\mu$
  $E^M_{out}(k) = E^M_{out}(k-1) - f^M(k).v^M(k)$
  $E^M_{in}(k) = E^M_{in}(k-1)$

gaps in the energies $E^M_{out}(k)$ and $E^S_{in}(k-T_b)$ known as passivity-gaps, since the force reduction is dissipating energy in this direction, see Fig. 2(b). Depending on the passivity-gap, $E^S_{in}(k-T_b) \geq E^M_{out}(k)$, the PC_{imp} will be triggered at a lower frequency or not at all. The passivity-gap could increase, decrease or remain constant depending on the dynamics of the teleoperation system, including the activity of the human operator and the remote environment. A persistently increasing passivity-gap during the course of the delayed teleoperation can be undesirable, as it may prevent the triggering of PC_{imp} at critical moments, which could potentially destabilize the system. Several strategies could be employed to mitigate the artifact of increasing passivity-gap. For instance, the accumulated energy levels could be periodically reset at strategic instances such that, $E^M_{out}(k) = E^S_{in}(k-T_b)$, or an adaptive μ

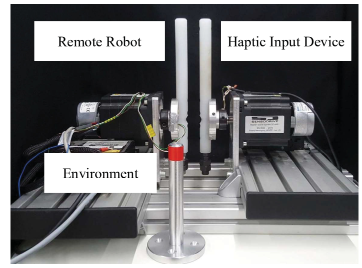


Fig. 3. Experimental setup: two 1-DoF haptic devices and the environment with position-force computed bilateral teleoperation architecture.

could be introduced to regulate the passivity-gap dynamically. However, it is important to emphasize that the present research does not focus on these techniques to mitigate the passivity-gap. Instead, it demonstrates the feasibility and effectiveness of the proposed perceptual-based method, which leverages human haptic perception limitations to improve haptic feedback performance while preserving the fidelity of force feedback. Note that the PO and PC on the secondary side remains unchanged. Also that the scaling μ is not introduced during $E^M_{in}(k)$ phase.

The experimental results of the proposed method is presented in Section IV to demonstrate the reduction of force chattering while minimizing the perceptible degradation of haptic quality for the human operator.

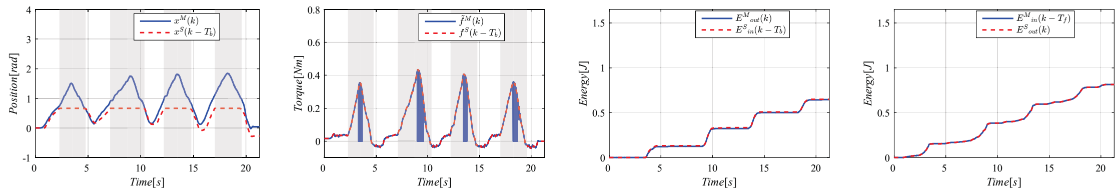
IV. Experiments

A. Experimental Setup

Figure 3 shows the experimental setup with position-force computed teleoperation architecture, wherein the velocity command from the 1-DoF haptic device is transmitted through the CC to the 1-DoF remote robot. On the secondary side, a proportional-derivative (PD) controller computes the control force, which is then relayed back to the haptic device to provide force feedback to the human operator. The TDPA and proposed method was implemented in MATLAB/ Simulink at a sampling rate of 1 kHz. For the experiments, a human operator controlled the 1-DoF haptic input device to teleoperate the remote 1-DoF robotic system, making four consecutive contacts with a rigid object. The coupling gains were k_p = 310 N.mm/rad, k_d = 10 N.mm.s/rad. The ϵ was chosen as 20% [32], and therefore the scaling factor μ = 0.80 made the vibrations hardly perceptible to the human operator with the 1-DoF haptic device used in the experiments. To evaluate the performance of the proposed method, intentional communication delays of 200 ms and 500 ms were introduced.

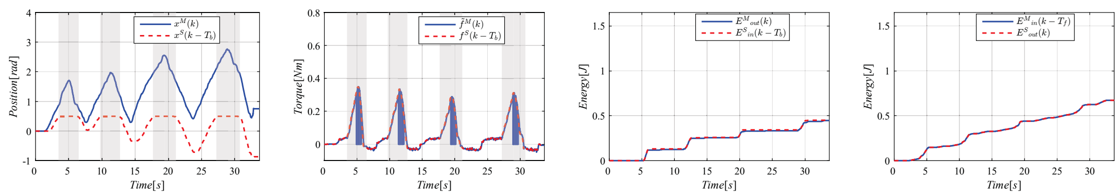
B. Experimental Evaluation

To evaluate of the proposed method, conventional TDPA was selected as a benchmark for comparison. This is because TDPA is well-established, frequently referenced, and extended in numerous researches. By using TDPA as a comparative standard, the performance of the proposed controller can be effectively demonstrated, offering a familiar context for understanding the advancements introduced.



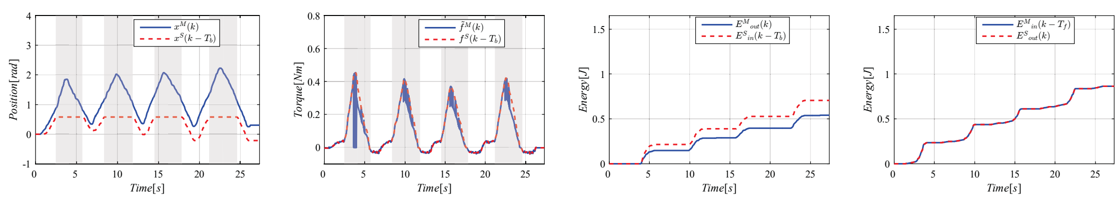
(a) (b) (c) (d)

Fig. 4. TDPA with 200 ms RT delay: (a) position, (b) force, (c) observed energies on the main side, (d) observed energies on the secondary side.



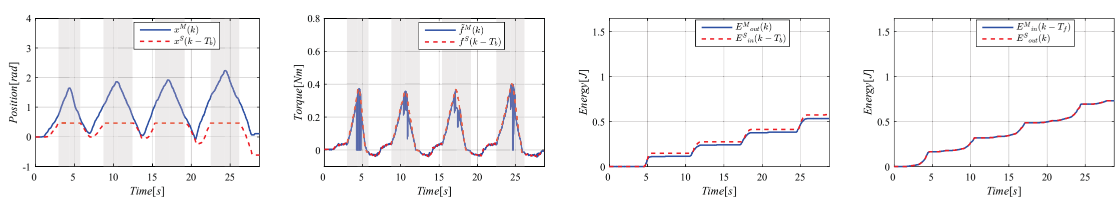
(a) (b) (c) (d)

Fig. 5. TDPA with 500 ms RT delay: (a) position, (b) force, (c) observed energies on the main side, (d) observed energies on the secondary side.



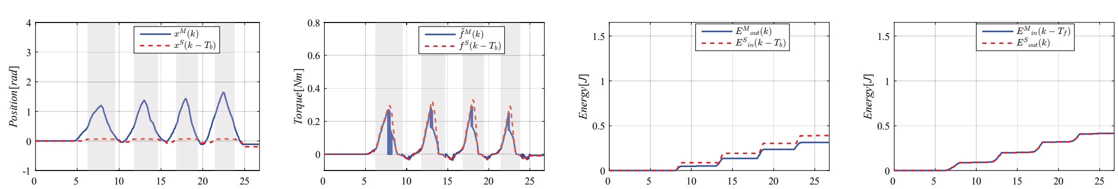
(a) (b) (c) (d)

Fig. 6. Proposed perceptual-based method with 200 ms RT delay: (a) position, (b) force, (c) observed energies on the main side, (d) observed energies on the secondary side. The shaded region shows the wall contact. The shaded region shows the wall contact.



(a) (b) (c) (d)

Fig. 7. Proposed perceptual-based method with 500 ms RT delay: (a) position, (b) force, (c) observed energies on the main side, (d) observed energies on the secondary side. The shaded region shows the wall contact.



(a) (b) (c) (d)

Fig. 8. Proposed perceptual-based method and OBG approach with 500 ms RT delay: (a) position, (b) force, (c) observed energies on the main side, (d) observed energies on the secondary side. The shaded region shows the wall contact.

Figures 4 and 5 illustrate the experimental results for the TDPA under round-trip (RT) communication delay of 500 ms. These plots exhibit typical TDPA behavior [14], wherein the PC_{imp} introduces high-frequency chattering on the main side, while the PC_{adm} leads to position drift on the secondary side. The high-frequency chattering arises due to the adaptive damping element being triggered at a high rate when the PO on the main side detects $E^M_{out}(k) > E^S_{in}(k - T_b)$. Similarly, the observed position drift results from the adaptive damping element acting on the delayed reference velocity due to the PO on the secondary side detecting $E^S_{out}(k) > E^M_{in}(k - T_f)$. A comparison between Figs. 4(b) and 5(b) reveals that high-frequency chattering worsens as communication delay increases from 200 ms to 500 ms. Likewise, Figs. 4(a) and 5(a) shows that position drift also exacerbates with increased delay. The corresponding energy plots (Figs. 4(c), 4(d) 5(c), 5(d)) confirm that the system remains passive throughout the experiments.

Figures 6 and 7 present results for the same experimental conditions but with the proposed perceptual-based method. Comparing Figs. 4 (TDPA) and 6 (proposed method), it is evident that the high-frequency chattering induced by PC_{imp} is significantly reduced. This reduction is attributed to $f^M(k) = \mu f^S(k - T_b)$, which decreases $E^M_{out}(k)$, thereby introducing a passivity-gap, see Fig. 6(c).

The presence of this passivity-gap prevents PC_{imp} from triggering, effectively mitigating chattering. Notably, the experimental results show that PC_{imp} is triggered only during the first contact with the object, after which the accumulated passivity-gap obviates further activations. This initial activation occurs because no passivity-gap exists at the beginning of the interaction. A similar trend is observed when comparing Figs. 5 (TDPA) and 7 (proposed method) under a 500 ms delay. The reduction in high-frequency chattering is evident when analyzing the torque plots (Figs. 5(b) vs. 7(b)). Once again, PC_{imp} is triggered during the initial contact due to the absence of an initial passivity-gap, but its activation frequency decreases thereafter as the gap accumulates.

For further performance enhancement, the proposed method is combined with OBG approach [25], as shown in Fig. 7(b) for a 500 ms communication delay. Comparing Figs. 7(b) and 8(b), the reduction in chattering is evident, with PC_{imp} being activated only during the first contact and remaining inactive for subsequent interactions. This improved performance results from a greater accumulation of passivity gaps, as illustrated in Fig. 8(c). The OBG method modulates force feedback profiles based on the deflection of the virtual spring in the coupling controller. The characteristic force profile of OBG is evident in Fig. 8(b) (e.g., between 13 s - 14 s), where the force decreases during the releasing phase as the human operator withdraws from contact. This reduction in force assists the proposed method to further decrease $E^M_{out}(k)$ and expand the passivity-gap, thereby suppressing PC_{imp} activation. The small force vibrations observed in Figs. 6(b), 7(b), and 8(b) arise due to the PO switching between $E^M_{out}(k)$ and $E^M_{in}(k)$ phases. During the $E^M_{out}(k)$ phase, the delayed feedback force is scaled by μ=0.8, while in the $E^M_{in}(k)$ phase, it is not scaled (μ=1), which causes the force vibrations.

A comparative analysis of the NRMSE for force was conducted for conventional TDPA (0.119), the proposed controller (0.071), and the proposed controller with OBG (0.042088) using the 500 ms RT delay data. This analysis focused on the regions with passivity-gaps (wall contacts 2, 3, 4 in Figs. 5, 7, 8), demonstrating a clear reduction in vibrations, as evidenced by the minimized variations between $\tilde{f}^M(k)$ and $f^S(k - T_b)$.

It is important to highlight that the proposed method minimally affects the position drift between the commanded and reference positions, as $E^M_{in}(k)$ remains unmodified. The method is designed solely to mitigate chattering on the main side. Moreover, as discussed in Section III-B, no techniques were applied to artificially reduce the passivity gap. The results presented here serve as a proof of concept, demonstrating that the perceptual-based method effectively reduces high-frequency chattering induced by PC_{imp} with minimal implementation complexity on the main side.

V. Conclusion and Future Work

This paper presents a novel perceptual-based scaling method for TDPA, leveraging human haptic perception limits to mitigate high-frequency force chattering induced by conventional impedance-type passivity controllers PC_{imp}. By incorporating Weber's law into the framework, the proposed method strategically modulates delayed feedback force during energy-out phase on the main side, $E^M_{out}(k)$. The force modulation reduces $E^M_{out}(k)$, resulting in a passivity-gap between $E^M_{out}(k)$ and $E^S_{in}(k - T_b)$. This passivity-gap reduces the activation of the PC_{imp} while preserving overall system passivity. Experimental validation on a 1-DoF teleoperation system with delays of 200 ms and 500 ms RT, demonstrated that the method effectively suppresses high-frequency chattering, thereby improving haptic transparency and enhancing user experience. Compared to the conventional TDPA, the proposed method significantly reduced the chattering. The force plots indicated that with the proposed method, PC_{imp} activation was largely limited to the initial contact with the remote environment, after which the accumulated passivity gaps prevented further activations. Additionally, integrating the proposed method with OBG approach further improved force consistency, as observed in the reduced oscillatory behavior in the force response.

Although the proposed method considerably reduces force chattering, minor residual vibrations persist due to the switching between energy-in and energy-out phases at low velocities of the haptic device. While imperceptible to most human operators, still future work will explore strategies to mitigate these residual vibrations by considering energy reflection and energy reset. Additionally, a user study could be conducted to evaluate the effectiveness of the method across different WF. A comparative analysis with VMS filter, perceptual deadband with TDPA, and chattering-free method will further establish the relative advantages and limitations of the proposed method.

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