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Time-Domain Passivity-based Controller with an Optimal Two-channel Lawrence Telerobotic Architecture*

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Abstract— **The time-domain passivity approach has been proposed in the literature in a variety of formats to guarantee the stability of teleoperation leader-follower systems. The conventional use of the proposed technique utilizes the control effort at the follower side as the force feedback to be sent back to the user at the leader's side. However, this has resulted in transparency problems, especially when the follower dynamics are not negligible. On the other hand, four-channel and three-channel Lawrence architectures have been investigated widely in the literature to maximize the transparency of the system when, in most advanced cases, stability is guaranteed using wave-variables. However, wave-variables are historically known for their transparency deterioration problems. In this paper, we propose a two-layer approach taking advantage of the fusion of (a) a more optimal derivation of Lawrence telerobotic architecture (utilizing only two channels), and (b) a two-port time-domain passivity stabilizer while comparing the performance with a one-port passivity stabilizer. The two-channel derivation of the Lawrence architecture allows for implementing a two-port time domain passivity approach, which is investigated in this paper. The performance of this is compared systematically through a multi-objective approach by analyzing dissipated energy besides force and velocity errors for a wide range of time delays and frequencies of excitation. The paper gives a comprehensive view of the efficacy of two-port versus one-port time-domain passivity control when combined with the two-channel derivation of Lawrence architecture.**

I. Introduction

This paper is written at the time of the COVID-19 pandemic when a wider range of in-person activities, including those in healthcare systems, have been affected by social distancing guidelines. The current situation has again highlighted the importance of remote rendering and remote manipulation with a particular application, including but not limited to healthcare. This paper aims at a comprehensive analysis of a major bottleneck of the telerobotic system, which has been an active area of research during the last two decades, i.e., the stability of highly-fiddle telerobotic systems that enable force reflection for the operator allowing for precise conduction of remote manipulation.

The wide-range applications of teleoperation, in telerobotic surgery, telerobotic rehabilitation, and space technologies, has attracted a great deal of interest in the last three decades. However, the stability of such technology has been a challenge, which has resulted in solutions reducing the transparency of the system, which have limited translational efficacy for highly-sensitive tasks, including surgery and rehabilitation [1]–[4]. In this regard, a wide range of stabilizers has been proposed for teleoperation, including wave variables [5]–[7], time-domain passivity control [2], [4], [8]–[17], and small-gain controllers [3], [18], [19]. Two of the authors of this paper have contributed to the field by proposing controllers to improve transparency from various perspectives while guaranteeing stability [2]–[4], [20], [21].

Transparency and stability are two main properties to be maximized using control architectures; however, the literature for maximizing both are in most cases decoupled, meaning that in some papers, the main focus is on developing stability guaranteeing schemes, and in some papers, transparency is investigated (while minimizing the complexity of the system) and a stability "condition" is introduced instead of stabilization. The current paper introduces a novel feature that fuses transparency and stability, focusing on a systematic analysis of the behavior of the system from a multi-objective perspective, including frequency of excitation and delay.

The very early telerobotic architectures utilize two-channel schemes, without providing pure transparency even in the absence of time delay, due to the effect of uncanceled interconnected dynamics of the system [22]. In order to improve transparency, a four-channel teleoperation architecture was proposed, known as Lawrence Four-Channel (LFC) [22], canceling the residual interactional dynamics and guaranteeing maximum achievable transparency. The two main issues with the initial design of the LFC scheme were (a) the complexity of the system caused by the need to exchange four-channel information between the leader and follower robots, and (b) the stability concern as the resulting fully transparent architecture was on the boundary of stability, which could be lost by even a small amount of delay.

In order to address the aforementioned issues, an Extended LFC (ELFC) architecture was proposed adding local feedback loops, which allows for (a) eliminating one communication channel, (b) preserving the perfect transparency, (c) reducing the complexity of the system due to elimination of several loops, and (d) allowing for a stability margin

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which is quantifiable to assess the expected behavior of the system in the presence of time delays [23]. Accordingly, two simplified, perfectly transparent three-channel architectures were designed, and the stability of the architecture was evaluated using linear control theory [23], [24].

The three-channel telerobotic scheme was modified in [4], reducing the number of channels to two while (a) preserving the perfect transparency, and (b) relaxing the assumption of linear dynamics and passivity of the operator's biomechanics and the environment, based on small-gain control theory. In this regard, the two-channel Modified-ELFC (MELFC) architecture has been achieved as the simplest transparent architecture [4]. Using MELFC architecture, the stability of the system only depends on the input-to-output stability (IOS) gain of the operator's biomechanics versus IOS gain of the environment, regardless of other dynamic loops in the system. If the IOS gain of the operator is larger, the system will be stable regardless of the existence of the communication delay. This simplified condition is achieved due to the elimination of the 3rd communication channel.

When the stability condition is to be violated, due to the specific characteristics of the task, a control architecture is needed to guarantee the stability of the system. In MELFC teleoperation, the instability is caused by the non-passivity of the communication delay, which results in accumulation of energy, which may not be compensated with the existing damping in the system (which could be minimized for a better fidelity of the force field), resulting in instability.

In order to guarantee the stability of the generic (not MELFC) teleoperation system, significant research has been conducted based on control passivity theory. The aim of stabilizers is to inject damping to dissipate extra energy to solve the stability issue of delayed teleoperation systems. It should be noted that the higher the damping, the more distortion there will be of interactive modalities, and deterioration of system transparency. Thus there is always a trade-off between stability and transparency [22]. Various architectures have been proposed in the literature [25], [26], each of which is different in terms of calculation of the needed damping and injection mechanism for the damping (one-port versus two-port). As one existing solution, Wave Variable Transformation (WVT) was initially proposed for a generic (not MELFC) two-channel telerobotic architecture to guarantee stability of teleoperation systems by transforming the velocity and force signals into wave variables for transmission [6], [7]. Due to the flexibility of the particular mathematical derivation of WVT, it has been generalized to be used for LFC architectures [5], [6]. However, this stabilizer is known for its conservative stability, which significantly deteriorates the transparency of the system partly due to the production of periodic reflective waves of forces in the feedback channel.

In order to enhance the transparency of generic time-delayed teleoperation, the Time-Domain Passivity Approach (TDPA) has been introduced in the literature in both energy and power domains [9], [12], [14]–[16], [27]–[29]. This stabilizer observes the flow of the energy or interactional power, and then adaptively dissipates the excess energy produced by the communication delay through the administration of adaptive damping into the system to make the system passive. The aforementioned TDPA can be used in one-port for haptic system [29] and two-port for teleoperation [9], [28] configurations. Extensive research has been conducted in the literature to improve the functionality of TDPA. In this regard, reference energy following [30] and power-based TDPA [16] have been suggested to smooth the PC control action. Drift compensation [14], [31], and position synchronization [15] methods have been proposed to solve position drift. Energy reflection consideration has been introduced to reduce the conservatism of the PC [12]. An observer-based gradient controller has also been introduced to improve the performance [8]. Each of the mentioned efforts has taken a valuable step in improving the performance of TDPA.

For teleoperation systems, TDPA cannot be directly used for a four- and three-channel teleoperation system. Some architectural modifications have been proposed to implement TDPA indirectly for such teleoperation systems [32]. Thus, despite the benefit of this stabilizer, it has only been implemented on generic two-channel teleoperation when the control effort at the follower side (not the environmental measured reflective force) is sent back to the leader side robot, which, even in the absence of any instability significantly deteriorate the perception for the user. With the development of the two-channel MELFC, which maximizes transparency and operates on the measured environmental force (not the control effort of the follower robot), in this paper, for the first time, the MELFC is fused with TDPA, guaranteeing stabilization after maximizing transparency.

II. Two-channel Modified Extended Lawrence Architecture

A two-port leader-follower system, shown in Fig. 1, can be represented by a hybrid model as follows, in which the hybrid matrix represents the equation of the teleoperation system.

$$\begin{bmatrix} f_h \\ -v_e \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} v_h \\ f_e \end{bmatrix} \tag{1}$$

In (1), f represents the force, v represents velocity, h represents the human operator, and e represents the environment. Also h_{11}, h_{12}, h_{21}, h_{22} are the elements of the hybrid matrix of the system. Writing the interactional equations of the system [3], [23] and solving for v_h and v_e we have

$$v_h = \frac{1}{Z_l}(f_h - c_l v_h - f_e e^{-sT}) \tag{2}$$

$$v_e = \frac{1}{Z_f}(c_1 v_h e^{-sT}) \tag{3}$$

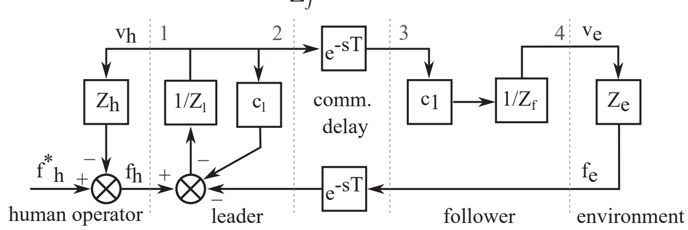

Fig. 1. Two-channel MELFC architecture

in (2) and (3), Z_l and Z_f are the imposed dynamics of the leader and follower side robots after feedback linearization [2]. c_l, c_1, T are leader local position controller, leader to follower feedforward velocity gain, and communication delay, respectively. As a result, the parameters of hybrid matrix will be $h_{11} = Z_l + c_l$, $h_{12} = e^{-sT}$, $h_{21} = -c_1 e^{-sT}/Z_f$, and $h_{22} = 0$. An ideal transparency will be achieved if:

$$h_{11} = h_{22} = 0 \quad, h_{12} = e^{-sT}, and \quad h_{21} = -e^{-sT} \tag{4}$$

By choosing $c_l = -Z_l$ and $c_1 = Z_f$, it can be seen that equation (4) holds; therefore, the two-channel MELFC architecture shown in Fig. 1 is perfectly transparent.

The main different, when compared with the three-channel ELFC is the choice of local leader controller c_l, which can be shown that would results in having the conventional follower feedforward velocity gain to be equal to zero, relaxing the need for having an additional communication channel [23].

III. Time Domain Passivity Controller

According to passivity theory, a system is stable as long as the energy produced by the system is less than the summation of initial energy and ports' energy as shown in (5).

$$E(t) - E(0) \leq \int_0^t \sum_{i=1}^{n} f_i(t) v_i(t) dt \tag{5}$$

The above-mentioned derivation is exploited in the discrete-time domain in TDPA, using which a passivity observer (PO) tracks the flow of energy of the ports, and a passivity controller (PC), generates variable damping to dissipate the excess energy (the initial energy of the system has been assumed zero) violating the passivity condition to make the system passive and thus stable [29].

Remark: *One-port TDPA has been used mainly for haptic systems when the follower and environment are virtual and there is no communication delay. However, as will be evaluated later in this paper, it is important to note that the same stability scheme (one-port) can be used for stabilizing of telerobotic systems. In this way, the one-port system of Fig. 2(a) will include the follower-communication-environment compound interactive dynamics. This means that after implementing the MELFC in this paper, we place a passivity observer and controller at the human side. The observer will determine the delivered energy from the environment through the communication, and the passivity controller will treat the environment-communication-follower interaction as a whole, guaranteeing the flow of total system energy and resulting in guaranteeing the stability of the system. Since the finer energetic behavior at the leader side is not considered using this scheme, we hypothesize that the one-port TDPA will behave in a more conservative manner, dissipating more energy, when compared with the two-port TDPA.*

For the one-port system, as shown in Fig. 2(a), the passivity criterion for the system has been derived [29] as:

$$E_{sys}(n) = E_2^{L2R}(n) - E_2^{R2L}(n) = \Delta t \sum_{0}^{n} (P_2^{L2R}(k) - P_2^{R2L}(k)) \geq 0 \tag{6}$$

in which E_{sys}, E_2^{L2R}, E_2^{R2L}, P_2^{L2R}, P_2^{R2L}, Δt are the system's energy, left to right side energy of port #2 (input energy to the system), right to left side energy at port #2 (output energy from the system), input power of port #2, output power of port #2, and sample rate, respectively. Also, we have

$$P_2^{L2R}(n) = \begin{cases} f_2(n)v_1(n) & if \;\; f_2(n)v_1(n) > 0 \\ 0 & if \;\; f_2(n)v_1(n) \leq 0 \end{cases} \tag{7}$$

$$P_2^{R2L}(n) = \begin{cases} -f_2(n)v_1(n) & if \;\; f_2(n)v_1(n) < 0 \\ 0 & if \;\; f_2(n)v_1(n) \geq 0 \end{cases} \tag{8}$$

when $f_2(n)v_1(n)$ is the power of port #2. Thus, as long as the observed energy (E_{obs}) is positive, the system is passive and stable, and the controller will not get activated, resulting in zero injected damping. However, negative E_{obs} shows that the port is showing non-passivity and the amount of generated energy is equal to $-E_{obs}$. In this condition, a passivity controller regulates the energy flow of the system delivered from the environment through the communication by dissipating excessive energy.

$$f_l(n) = f_{fd}(n) + \alpha(n) v_l(n) \tag{9}$$

$$\alpha(n) = \begin{cases} \dfrac{E_{obs}(n)}{\Delta t . v_l^2(n)} & if \;\; E_{obs}(n) < 0 \\ 0 & if \;\; E_{obs}(n) \geq 0 \end{cases} \tag{10}$$

$$E_{obs}(n) = E_2(n) \tag{11}$$

In (9-11), f_l, f_{fd}, α, v_l, E_{obs} are leader force, delayed follower force, variable damping factor, leader velocity, and observed energy, respectively. Writing the stability equation leads to the inequality below, which proves the stability (more details can be found in [2], and in general for TDPA, more details can be found in the literature [29]):

$$E_1(n) = \Delta t \sum_{0}^{n} f_l(k) v_l(k) \geq 0 \tag{12}$$

For the two-port system shown in Fig. 2(b), the passivity criterion can be derived as follows [9], [12]:

$$E_{sys}(n) = E^{L2R}(n) + E^{R2L}(n) \geq 0 \tag{13}$$

$$E^{L2R}(n) = E_2^{L2R}(n) - E_3^{L2R}(n) \tag{14}$$

$$E^{R2L}(n) = E_3^{R2L}(n) - E_2^{R2L}(n) \tag{15}$$

If E^{L2R} and E^{R2L} are both positive, E_{sys} is also positive, and the system is passive. However, due to delay and causality, it is not possible to observe $E_2^{L2R}(n)$ on the right side, and $E_3^{R2L}(n)$ on the left side [33]. Only delayed values of them are observable on the opposite side. Thus, the observed energy on each side can be determined as:

$$E_{obs}^{L2R}(n) = E_2^{L2R}(n-T) - E_3^{L2R}(n) \tag{16}$$

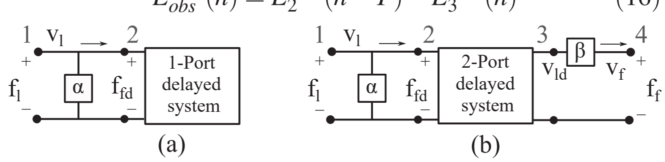

Fig. 2. (a) one-port system with impedance TDPA stabilizer, and (b) two-port system with impedance TDPA stabilizer on the left and admittance TDPA stabilizer on the right.

$$E_{obs}^{R2L}(n) = E_3^{R2L}(n-T) - E_2^{R2L}(n) \quad (17)$$

Because P_3^{R2L} and P_2^{L2R} are strictly positive, it can be shown that $E^{L2R} \geq E_{obs}^{L2R}$ and $E^{R2L} \geq E_{obs}^{R2L}$. So, if $E_{obs}^{L2R} \geq 0$ and $E_{obs}^{R2L} \geq 0$, it can be concluded the system is passive. This way, the two energy observers are decoupled, and the passivity can be verified on each side independently. As long as E_{obs}^{L2R} and E_{obs}^{R2L} are positive, the system is conservatively passive. However, the negative value of each of them represents energy generation in the system in the associated direction. In the operator side, an impedance type PC, as mentioned in (9), (10), and (11) with $E_{obs}(n)$ as in (17), has guaranteed passivity in the environment to operator direction similar to that in the one-port system [9].

$$E_1(n) = \Delta t \sum_{0}^{n} f_l(k) v_l(k) \geq 0 \quad (18)$$

On the environment side, admittance type PC as below can guarantee the passivity of the operator to environment direction:

$$v_f(n) = v_{ld}(n) - \beta(n) f_f(n) \quad (19)$$

$$\beta(n) = \begin{cases} \dfrac{E_{obs}^{L2R}(n)}{\Delta t . v_l^2(n)} & if \quad E_{obs}^{L2R}(n) < 0 \\ 0 & if \quad E_{obs}^{L2R}(n) \geq 0 \end{cases} \quad (20)$$

$$E_4(n) = \Delta t \sum_{0}^{n} f_f(k) v_f(k) \geq 0 \quad (21)$$

$$E(n) = E_1(n) + E_4(n) \geq 0 \quad (22)$$

In (19-22), v_f, v_{ld}, β, f_f, are follower velocity, delayed leader velocity, variable damping factor, and follower force. Thus, the passivity of the compounded system is guaranteed in the presence of an unknown time delay.

Remark: *Two-port TDPA has been used mainly for telerobotic systems when one passivity observer and a passivity controller are placed on both sides of the communication network. The design of two-port TDPA may be inspired by the two-port energy modulation of the wave variable approach. However, the difference is that the TDPA will directly observe the energy flow taking advantage of possible energy dissipative components of the system and will modify the energy when the passivity condition is to be violated. When compared with the one-port TDPA, it may be assumed that the two-port formulation may impose more conservatism in the system due to the existence of two dissipative factors and due to the implementation based on conservative simplification of energy exchange, as discussed. In other words, in some situations, although there might be some non-passive behavior observed in one direction, the compound behavior may still remain stable. However, it should be noted that the two-port formulation distributes the dissipation of the energy on the two channels of communication; however, the one-port system imposes all the dissipation on the force reflection to the operator. Thus, a systematic comparative analysis of the behavior of the two controllers is needed, particularly when the telerobotic architecture is designed to be MELFC. This analysis is conducted in the next section of this paper for the first time.*

IV. Passivity Based Stabilization of Two-channel MELFC Telerobotic Architecture

We propose a teleoperation system that combines the perfectly transparent two-channel MELFC architecture with two-port TDPA, and then we compare the performance of teleoperation when one-port TDPA is also implemented. As shown in Fig. 3, taking advantage of MELFC combined with a two-channel TDPA, the operator velocity is sent to the follower robot as feedforward signal, and the environment force is sent from the follower to the leader as the feedback. This is different from the conventional implementation of TDPA, where the control effort of the follower robot is sent back to the leader robot as the reflective force. As can be seen in Fig. 3, an admittance type TDPA is implemented on the follower side (right) to modify the velocity signal, and an impedance type TDPA is implemented on the leader side (left) to modify the force signal.

Two energy observers have been placed on the left and right ports of the communication channel. Each energy observer measures the input and output energy of the associated port separately. The input energy of each side is sent to the other side to be used in calculating E_{obs} of the opposite side. E_{obs}^{L2R} and E_{obs}^{R2L} derives as follows:

$$E_{obs}^{L2R}(n) = E_2^{L2R}(n-T) - E_3^{L2R}(n) + \Delta t \sum_{0}^{n} \beta(k) f_f^2(k) \quad (23)$$

$$E_{obs}^{R2L}(n) = E_3^{R2L}(n-T) - E_2^{R2L}(n) + \Delta t \sum_{0}^{n} \alpha(k) v_l^2(k) \quad (24)$$

In (23) and (24), the last terms are the total energy dissipated by the TDPA on each side. When the observed energy of each side is negative, the passivity controller on the same side enables to dissipate the excess energy. The left PC injects damping by modifying the feedforward force to the leader side. The right PC implies damping to the right side of the system by modifying the feedforward velocity signal to the follower. It should be noted that there has been a wide range of conducted experimental studies on the passivity behavior of human biomechanics based on which the passivity of the human operator can be considered [4], [10]. As a result, the TDPA would guarantee the stability of the two-port network connected to two passive elements, which will result in the stability of the interconnected system.

V. Simulation Design

For this paper, a wide range of simulations has been conducted to evaluate the efficacy of both one-port and two-port TDPA for a range of excitation frequencies and time delays. The compound dynamics of the system were solved using a fixed-step ODE4 solver, and the time step has been set to 10^{-5}. The excitation frequency is considered to be in the range of 0.2 to 3Hz, which corresponds to the frequency of human voluntary motions [34], [35]. Nine types of environment ($Z_e = B + K/s$), as shown in Table 1, are considered for conducting a comprehensive analysis of the system. To verify the performance of the system for different delays values, the communication delay values have been

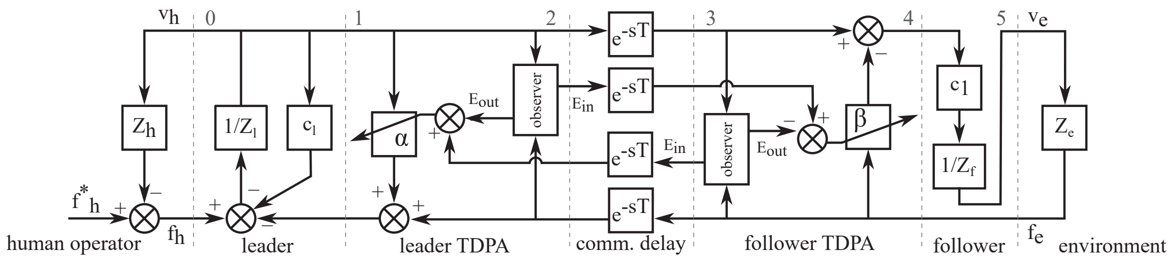

Fig. 3. MELFC architecture with two-port TDPA

chosen from 0 to 400 ms for round-trip. The impedance of the operator's hand is assumed as $Z_h = 50 + 250/s$.

TABLE I

IMPEDANCES OF THE INVESTIGATED ENVIRONMENTS

No.	1	2	3	4	5	6	7	8	9
B	0	12.5	25	50	100	200	400	800	200
K	0	62.5	125	250	500	1k	2k	4k	30k

The ground truth is determined by simulating the system without delays. In order to evaluate the performance of the system, one-port TDPA, two-port TDPA, and wave variables are simulated, and the root mean square of the force and velocity tracking errors are calculated. In order to directly evaluate the performance and transparency of the stabilized systems, the signals are shifted in time to compensate for the effect of delay on the analysis, and the resulting time-corrected signals are compared to do a comprehensive evaluation. Also, the dissipated energy of the system is evaluated to analyze the conservatism of the system.

VI. RESULTS AND DISCUSSIONS

Fig. 4 represents the "RMS of the modification (RMSM)" imposed by the controllers for operator velocity, environment velocity, operator force, and environment force in the environment #6 with respect to the ideal values when delay and frequency of excitation changes as mentioned in the above. Fig. 5 shows the "RMS of difference (RMSD)" between the leader force and the follower force, and between the leader velocity and follower velocity for a wide range of frequency of excitation and delay. It also demonstrates the total energy dissipated by the controller, representing the conservatism of the system. Fig. 6 represents the RMSD between the leader and the follower force and velocity for a fixed frequency of excitation (1.75 Hz) when the delay and the impedance of the environment change.

As shown in Fig. 4, interestingly, WVT represents the lowest force and velocity modification when compared to ideal transparency, for all simulated conditions. However, it should be noted that Fig. 4 is simulated for environment #6. This means that a different behavior would be observed if the environmental impedance changes. This important point is represented in Fig. 6, when the performance of WVT is compared with One-port and Two-port TDPA for a variety of environments. As can be seen in Fig. 6, for a softer environment, WVT has worse (high RMSD) for force tracking when compared with TDPA approaches. The same cannot be said from Fig. 6, about velocity tracking. As can be seen in Fig. 6, one-port TDPA has the overall best performance (minimum RMSD), in terms of velocity tracking, when compared with two-port TDPA and WVT.

In Fig. 4, on the follower side, the errors for the two-port TDPA and WVT systems are less than for the one-port TDPA, and the difference increases significantly when delay increases. However, two-port TDPA and WVT performed almost equally from that perspective with a small increase of error for TDPA for higher delays. The above-mentioned observation is not in agreement with the classical results for the performance of the one-port TDPA, illustrating the importance of such a simulation study. It was expected that velocity modifications should be smaller with the one-port TDPA. However, Fig. 4 shows force channel modification results in the deterioration in the velocity channel too, as they are connected in the teleoperation loop. From the better performance of the two-port TDPA and WVT in terms of RMSM, it can be inferred that division of the modifications between the force and velocity channels, results in less deterioration of the follower signals.

Fig. 5 demonstrates the RMSD between the leader and the follower signals, which directly contributes to the transparency of the systems. As expected, the force tracking of two-port TDPA is better than that of the one-port TDPA for almost all values of delays and frequency of excitation. This is due to the division of energy dissipation between the force channel and the velocity channel in two-port TDPA, which reduces the burden on dampening only through force modification. However, the velocity tracking is worse in the

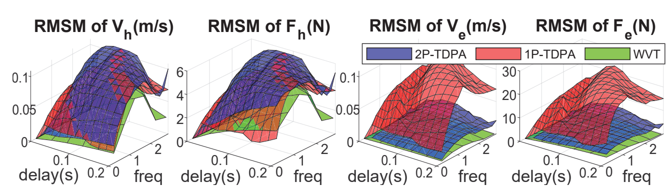

Fig. 4. RMSM of force and velocity of the two-port TDPA, one-port TDPA, and WVT for range of delays from 0 to 200ms (for each side), and range of frequencies from 0.2 to 3 Hz.

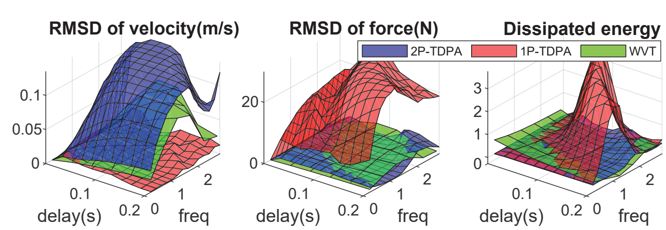

Fig. 5. RMSD between force and velocity of the leader and the follower, and total dissipated energy. Range of delays are from 0 to 200ms (for each side), and range of frequencies are from 0.2 to 3Hz.

two-port TDPA when compared with the one-port TDPA. This is reasonable, since the one-port TDPA put maximum burden on the force modulation and result in minimum deviation of velocity. When compared with WVT, the force tracking achieved by the two-port TDPA is almost equal to the WVT, and is better than the one-port-TDPA. In terms of velocity tracking, the one-port TDPA performed better than the WVT, and the two-port TDPA performed worse.

Energy dissipation is a measure of the amount of intervention of the controller in the system, and it can be interpreted as an indicator of the overall performance of the system. As shown in Fig. 5, the energy dissipation of the two-port TDPA is much smaller than the one-port TDPA for all delays and frequency of excitation. In comparison with the WVT, energy dissipation of the two-port TDPA is almost equal to the WVT for large delays and high frequencies, and smaller than the WVT for small delays and low frequencies. The variation of the energy dissipation is not uniform with variation in the delay and frequency. This was also not completely expected; however, the reason could be that the two-port TDPA and WVT divide modifications between force and velocity signals avoiding significant changes in the shape of each signal. This, results in less required intervention for stability. Also, it shows that one parameter cannot be the only indication of conservatism; thus, energy dissipation should be evaluated alongside force modification and velocity modification.

The difference between the results shown in Fig. 4 and 5 opens a discussion about the measurement of the performance of teleoperation systems. Transparency alone cannot provide a representation of the performance of the system. A teleoperation system may be transparent to a good extent; however, it may drastically change the shape of the energy exchange. Moreover, as can be seen in Fig. 4, 5, and 6, the change in the performance of the teleoperation system shows a non-uniform change with frequency and delay. The increase in delay and/or frequency have not absolutely reduced performance and transparency. There are areas with higher frequencies and delays, but with better performance and transparency in terms of all evaluations.

Thus, it should be noted that all of these analyses can be affected in a nonlinear manner by changing the delay and the magnitude of the environment impedance. As can be seen in most of the results, the changes with respect to delay or the frequency of excitation or the stiffness of the environment is neither linear nor monotonic. Thus, a comprehensive analysis of the performance should be conducted, taking into account the range of delays, frequency of excitation, and the stiffness of the environment for each particular task to choose the best stabilizer. In this paper, taking advantage of the two-channel MELFC we approach the maximum achievable transparency while evaluating the performance of the system.

The plots in Fig. 6 show the RMSD between the leader and follower force and velocity for the MELFC teleoperation architecture stabilized with one-port TDPA, two-port TDPA, and WVT. The environment axis shows the impedance of the environment based on the table given in the previous section. Accordingly, #1 is for a zero impedance environment (free motion), and #9 is for high impedance environments. The delay axis shows the amount of communication delay in ms. The velocity difference for the one-port TDPA is less than that for the others for all environmental impedances. This is due to the intrinsic perfect transparency of MELFC and one-port TDPA. However, the leader force to follower force difference drastically increases with the impedance of the environment. On the other hand, the two-port TDPA shows less difference between forces and high difference between velocities. When comparing the WVT with the two-port TDPA in terms of velocity difference, we can see that the performance of the two-port TDPA is better in soft environments. With the increase of the environmental impedance, the force tracking of the two-port TDPA deteriorates faster than the WVT. In contrast to TDPA, which shows the best performance in environment #1 (free motion), WVT shows its best performance in environment #4. This is due to the existence of a fixed damper in the WVT which has been tuned for environment #4 in our study.

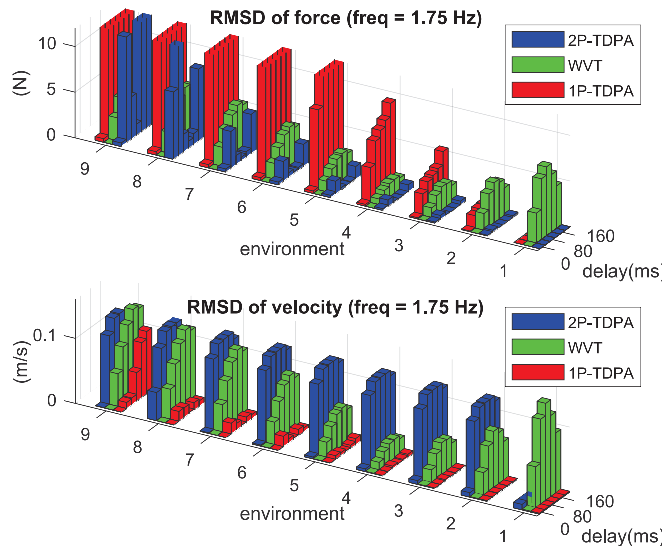

Fig. 6. RMSD between leader and follower force and velocity versus delay and environmental impedance. The environment axis shows the number of the associated environment. The increase in the environment number shows the increase in the environmental impedance. #1 is for a zero impedance environment(free motion), and #9 is for a high impedance environment (details are shown in Table 1). The RMSD of force for one-port TDPA for environment #5 to #9 is beyond the limit of the plot.

Importantly, and not completely aligned with the conventional understanding of the issue [20], Fig. 6 has shown that force and velocity transparency are not changing uniformly with delay. The force tracking of two-port TDPA is almost perfect (RMSD close to 0) with 80ms delay, but it deteriorates in delays below and over 80ms. On the other hand, WVT shows its worst (maximum RMSD) force transparency and velocity tracking when the delay is around 120ms. Increasing the delay over 120 ms, results in the better force and velocity tracking of WVT (this can better be seen in softer environments). Thus, it can be understood that the transparency of the MELFC teleoperation architecture stabilized with the two-port TDPA or the WVT is non-uniformly related to delay.

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