Reducing the conservatism of the time domain passivity approach through consideration of energy reflection in delayed coupled network systems [☆]

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ABSTRACT

The Time Domain Passivity Approach (TDPA), a method to inject adaptive damping to satisfy the passivity condition in real-time, has emerged as a powerful tool to stabilize coupled network systems with/without communication delay, such as haptic and teleoperation systems, due to its simplicity and effectiveness. However, we found that the conventional TDPA has unnecessary conservatism especially in delayed coupled network systems due to direction dependent energy calculation and dissipation. In this paper, we propose a new time domain passivity approach with reduced conservatism by considering the energy reflection from an energy storage element in the network. The method is generally formulated with a delayed 2-port network system including an energy storage element and implemented to a teleoperation system. The proposed method is experimentally tested and a comparison with the conventional TDPA reveals improved kinesthetic coupling and transparency in terms of position tracking and force reflection.

Keywords:

Time domain passivity control
Delayed coupled network system
Energy reflection
Teleoperation

1. Introduction

In recent years, there has been an increasing interest in time domain controllers that guarantee passivity online. In those methods, the system's energy is monitored in real time and the controller gain is adaptively tuned in order to satisfy the passivity condition in the time domain. The Time Domain Passivity Approach (TDPA) has triggered this area of research. The authors of [1] proposed the TDPA for haptic and coupled network systems. In [2], a time domain based method for passivity preserving discretization for haptic interaction was proposed. Also focusing the interaction with virtual realities, the inertia matrix of a multi degree of freedom haptic device served the weighting of a generalized variable passivity controller damping in [3]. In [4], the TDPA method was extended for teleoperation setups without delay. The TDPA for passivity control of the delay in a 2 Channel teleoperation system was introduced in [5]. The authors of [6–8] extended the TDPA for the application in more complex teleoperation architectures. In [9], the conventional TDPA has been applied to an industrial, multilateral, multi DoF teleoperation scenario.

Especially this type of online passivity guaranteeing controller has shown great advantages in stabilizing delayed coupled network systems.

Due to many unknown system parameters and the wide range of parameter variation in coupled network systems, their stabilization has been known to be quite complicated. A variety of control concepts as the wave variables method [10–12] were developed for delayed coupled network systems. The authors of [13] proposed a passive set point controller for time delayed teleoperation systems. An energy tank based two layer approach was introduced in [14]. Among them, TDPA has been getting more attention, and is recognized as one of the best performing control approaches compared to other types of controllers [15].

However, the TDPA has still been suffering from limited control performance due to its controller design conservatism. To satisfy the passivity condition in real time, it often over sacrifices the performance of the controller which can result in large position synchronization error and feedback force attenuation [16]. Recently, researchers have proposed a modified method to reduce the design conservatism of the TDPA, in particular for improved position synchronization in delayed coupled network systems such as teleoperation systems [17,18].

However, we recently found that there is still large room to improve the performance of the TDPA especially for network systems with delayed position coupling. The conventional TDPA passivates the network considering a direction dependent energy flow observation and control due

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to the limitation of the considered passivity proof [16]. However, we found that this causes unnecessary conservatism in the controller design because it didn't allow us to differentiate the reflected energy from the pure transmitted energy in the 2 port network.

In this paper, we propose a new method reducing the design conservatism of TDPA for coupled delayed network systems by avoiding the direction dependent energy monitoring. Therefore, a control loop in herent energy storage element is considered in the passivity controlled 2 port network. An ideal intended amount of energy in this energy storage element is determined and the overall passivity is guaranteed by limiting the energy output of the 2 port to the ideal energy content of the energy storage element in a direction independent manner. As the result, the required amount of energy dissipation for preserving overall passivity is minimized by *allowing energy reflection from the energy storage element*. It is important to note that, in contrast to [14] and [19], we consider potential energy but no dissipated energy in the energy storage element to achieve a physically reasonable interpretation of energy reflection.

This paper is structured as follows: Section 2 presents the fundamentals of Time Domain Passivity Control. Section 3 describes two state of the art approaches in TDPA of delayed 2 ports and the drawbacks resulting from the direction dependent energy monitoring. The proposed control concept for delayed coupled network systems and the respective stability proof are presented in Section 4. The advantages of the approach are discussed in a teleoperation setup employing experiments in Section 5. A performance comparison with a state of the art approach is presented in Section 6. Finally, Section 7 provides the conclusion.

2. Background

This section reviews the two conventional Time Domain Passivity Approaches for delayed coupled network systems and shows the sources of possible conservatism of these approaches, resulting especially from the direction dependent energy observation.

To guarantee the stability of a system with states x , the TDPA considers the passivity criterion:

$$V(x(t)) - V(x(0)) \leq \int_0^t s(u(\tau), y(\tau)) d\tau = \int_0^t y^T(\tau) u(\tau) d\tau. \quad (1)$$

As long as the energy increase ($V(x(t)) - V(x(0))$) in the system since $t = 0$ is not higher than the integral of the power (supply rate s , input u and output y) that has entered the system, the system hasn't generated energy itself. In other words, the system is passive and thus absolute stability can be guaranteed [20].

The passivity criterion is highly modular in that the passivity of a system is guaranteed if it consists of passive subsystems. The subsystems of a system can be designed with the help of the network representation. A network representation with clear causality and with a clear definition of the energy flow direction is essential for passivity based control methods as the TDPA. Especially in case of delayed coupled network systems, like time delayed teleoperation systems, the design of a proper network representation was not a trivial problem [6,8]. Figs. 1 and 2 show a 1 port and 2 port network, respectively. At each port, a power conjugate pair of effort variable (force) and flow variable (velocity) can be defined and measured. By integrating this power conjugate pair over time, the total energy can be calculated. Also, considering the sign of the conjugate pair, the energy flow direction can be determined.

A network representation of a delayed coupled network system is depicted in Fig. 3. The electrical models of human operator h , master device m , controller c , slave s and environment e consist of mass M (inductance), stiffness K (capacitor) and damping B (resistor) elements. The TDPA that can handle variable delay, jitter as well as package loss [5,21], assures the passivity of the communication channel (CC) through

Fig. 1. 1-Port Network.

Fig. 2. 2-Port Network.

so called passivity controllers (PC). The PCs terminate the passivity controlled delayed 2 port of the CC (port 2 and port 3).

Note that in a delay free system, the passivity criterion is not a conservative method since generally an intrinsically passive position controller is applied. The terminations of the network, Agent $\Lambda 1$ and Agent $\Lambda 2$ have to be designed in a passive manner. In case of teleoperation systems, Agent $\Lambda 1$ represents the human operator and the master device and Agent $\Lambda 2$ the slave in its environment. These terminations are obviously not passive but there is a widely accepted assumption that human operator and environment behave passive in their interaction such that the energy introduced by one is dissipated by the respective other. This assumption can be strengthened by the observation that, in real interactions, a human is used to use passive devices in active environments.

The direction of power flow (left to right L2R, right to left R2L) at a network subsystem port i can be distinguished by the sign of the power in time step k :

$$P_i^{L2R}(k) = \begin{cases} 0, & \text{if } P_i(k) < 0 \\ P_i(k), & \text{if } P_i(k) > 0 \end{cases} \quad (2)$$

$$P_i^{R2L}(k) = \begin{cases} 0, & \text{if } P_i(k) > 0 \\ -P_i(k), & \text{if } P_i(k) < 0 \end{cases} \quad (3)$$

with the power P_i

$$P_i(k) = v_i(k) F_i(k) \quad (4)$$

calculated from the force F_i and the velocity v_i at port i . By integration over time, the respective energies $E_i^{L2R}(k)$ and $E_i^{R2L}(k)$ can be calculated:

$$E_i^{L2R}(k) = T_s \sum_{j=0}^k P_i^{L2R}(j), \quad (5)$$

$$E_i^{R2L}(k) = T_s \sum_{j=0}^k P_i^{R2L}(j), \quad (6)$$

with the sampling time T_s . The passivity criterion of a 2 port as depicted in Fig. 2 is

$$E^0 + E_1^{L2R}(k) + E_2^{R2L}(k) \geq E_1^{R2L}(k) + E_2^{L2R}(k) \quad (7)$$

with the initial energy content E^0 of the 2 port network.

In the following, the TDPA control principles will be explained considering a basic teleoperation scheme. Fig. 4 presents a position computed force (PF_{comp}) architecture in which a desired velocity (and position) and the computed controller force are exchanged through the communication channels which are affected by communication delay T_1 in L2R and T_2 in R2L direction. The PI coupling controller (Ctrl) which penalizes the velocity and position deviation of the two agents is located on the right side of the CC. In this case, the potential energy storage in the network results from the controller spring that aims the position synchronization of the coupled devices.

Fig. 5 presents the signal flow diagram of the TDPA [17] in a simple PF_{comp} architecture. Through passivity observers (PO) on the left (L) and right (R) side of the CC, the energy behavior of the communication channel can be analyzed. The energy difference across a 2 port in one direction of energy flow can be observed and the energy

Fig. 4. Signal Flow Diagram of a PF_{comp} Architecture.

Fig. 5. Signal Flow Diagram of Time Domain Passivity Control for Approach 1.

$W^{PC1}(k)$ and $W^{PC2}(k)$ that has to be dissipated in time step k can be determined.

Passivity controller PC1 applies a variable damping to vary the force F_2 sent to the master device. At port 3, a velocity is sent in L2R direction from Agent A1 to the controller. Therefore, an admittance type PC2 is applied at port 3 in Approach 1 that injects a variable damping to vary this velocity signal. The depicted approach will be later referred to as Approach 1. Current implementations of time domain passivity control [7,8,22] consider such a combination of impedance and admittance type controllers.

An admittance type PC dissipates the energy $W^{PC2}(k)$ by a variation of the velocity v_3 :

$$v_4(k) = v_3(k) - \beta(k)F_3(k) \quad \text{with} \quad (8)$$

$$\beta(k) = \begin{cases} \frac{-W^{PC2}(k)}{T_S F_3(k)^2} & \text{if } W^{PC2}(k) < 0 \\ 0 & \text{if } W^{PC2}(k) \geq 0. \end{cases} \quad (9)$$

An impedance type PC dissipates energy by a variation of the force F_2 :

$$F_1(k) = F_2(k) + \alpha(k)v_2(k) \quad \text{with} \quad (10)$$

$$\alpha(k) = \begin{cases} \frac{-W^{PC1}(k)}{T_S v_2(k)^2} & \text{if } W^{PC2}(k) < 0 \\ 0 & \text{if } W^{PC2}(k) \geq 0. \end{cases} \quad (11)$$

Without loss of generality, we can say that there is always at least one energy storage element in a coupled network system. The energy storage elements can be position coupling or force controllers and can be located

Fig. 3. Network Representation of a Delayed Coupled Network System.

on the left and/or the right side of the communication channel. Here, we focus on systems with a position coupling control element on the right side of the CC as it is applied in teleoperation systems with PF_{comp} architecture. The adequacy of the proposed approach to other setups has to be further investigated in future. Still, the PF_{comp} architecture can be applied in several delayed coupled networks with arbitrary agents that can be designed as passive subsystems. Note that in non teleoperation systems, a desired motion trajectory with open loop control may cause an energy input to the coupled network. But, this energy input can be considered in the supply rate s , that does not violate the passivity condition (1). Therefore, the proposed approach can be applied to a large variety of applications.

3. Problem definition

Figs. 6 and 7 visualize how the conventional TDPA passivates delayed coupled network systems for two different ways of energy storage element consideration in the network. The Approach 1, presented in Fig. 6, excludes the energy storage element from the passivity analysis based on the assumption that the energy storage element does not

Fig. 6. Energy Observation and Passivity Control of Approach 1 [17].

Fig. 7. Energy Observation and Passivity Control of Approach 2 [5,24].

break the passivity condition due to its intrinsic passivity. However, it prevents the consideration of the extra energy dissipation ability of the energy storage element and applies an admittance type PC which can lead to position drift. In contrast, the other conventional Approach 2 (see Fig. 7) includes the energy storage element in the passivity analysis and avoids admittance type PCs. For both cases, the TDPA is applied to dissipate an excessive amount of energy that is generated by the delayed 2 port, which potentially leads to instability.

3.1. Functional principle of conventional approach 1

In [17] (Approach 1, Fig. 6), two PCs terminate the delayed two port (port A, B) which contains the communication channel (CC). The energy flow in the system is presented by thick arrows that are marked with light gray (right to left: R2L) and dark gray color (left to right: L2R). The clock indicates delayed communication. In each direction of energy flow, an energy monitoring unit (battery like shape) is charged from the input power into the delayed 2 port (thin dark gray line at port A in L2R direction and thin light gray line at port B in R2L direction). The energy monitoring unit contains the available amount of energy that is allowed to leave at the respective output side of the delayed 2 port. On the output side, two passivity controllers (thin dark gray line at port B in L2R direction and thin light gray line at port A in R2L direction) assure via energy dissipation that not more energy than the available amount of energy in the respective monitoring unit leaves the 2 port in the respective direction. However, one interesting behavior of the energy storage element is that a part of the energy is transmitted through the storage element to the respective other side whereas the rest of the energy is reflected back as it is shown by the split arrows inside the storage element. Therefore, the R2L energy flow at port B contains the reflected part of the energy from the L2R energy flow at port B. The energy reflection and transmission will be analyzed in more detail in Section 3.3.

The network representation of a PF_{comp} architecture with delay (compare signal flow diagram of Fig. 4) for Approach 1 is presented in Fig. 3. Here, the position controller (Ctrl) represents the energy storage element. Considering Fig. 3 and assuming a zero initial energy $E^0 = 0$, the passivity condition (7) is fulfilled, if

$$E_1^{L2R}(k) + E_4^{R2L}(k) \geq E_1^{R2L}(k) + E_4^{L2R}(k). \quad (12)$$

Due to the delay, this condition has to be split into two parts

$$E_1^{R2L}(k) \leq E_4^{R2L}(k - T_2) \quad (13)$$

and

$$E_4^{L2R}(k) \leq E_1^{L2R}(k - T_1). \quad (14)$$

Since the energies are monotonously increasing, conditions (13) and (14) fulfill condition (12). The passivity controller PC1 and PC2 of Approach 1 assure that condition (13) and (14) respectively are met. The energy that has to be dissipated can be calculated with

$$W^{PC1}(k) = E_4^{R2L}(k - T_2) - E_1^{R2L}(k) - W_{diss}^{PC1}(k - 1), \quad (15)$$

$$W^{PC2}(k) = E_1^{L2R}(k - T_1) - E_4^{L2R}(k) - W_{diss}^{PC2}(k - 1), \quad (16)$$

where W_{diss}^{PCi} ($i \in \{1, 2\}$) is the energy that has already been dissipated by the passivity controllers:

$$W_{diss}^{PCi}(k - 1) = W_{diss}^{PCi}(k - 2) + W^{PCi}(k - 1). \quad (17)$$

3.2. Functional principle of conventional approach 2

In contrast, in [5,23–25] (Approach 2, Fig. 7), the energy storage element is considered together with the CC in the passivity control. Thus, the two PCs are located on the left side of the CC (port A) and the right of the storage element (port C). Instead of the right side input into the CC (port B), the power input to the storage element on the right side (port C) is charged as the available amount of energy into the energy monitoring unit (battery like shape) in R2L direction. Analogous to Approach 1, two PCs assure via energy dissipation that not more energy than available in the energy monitoring unit leaves the 2 port in the respective direction. Again, the energy dissipation of the PCs can be over conservative because the energy observation is direction dependent and doesn't discriminate the directly reflected energy in the storage element.

Fig. 8 depicts the network representation of Approach 2. The PCs terminate the passivity controlled delayed 2 port including CC and the storage element (port 2 and port 4). These passivity controllers apply a variable damping to vary the forces sent in the respective directions (impedance type PC).

Analogous to Approach 1, the passivity controllers of Approach 2 assure that the conditions

$$E_1^{R2L}(k) \leq E_5^{R2L}(k - T_2) \quad (18)$$

and

$$E_5^{L2R}(k) \leq E_1^{L2R}(k - T_1) \quad (19)$$

are fulfilled which meets the passivity condition of the 2 port between port A and C with zero initial energy $E_0 = 0$ despite delay:

$$E_1^{L2R}(k) + E_5^{R2L}(k) \geq E_1^{R2L}(k) + E_5^{L2R}(k). \quad (20)$$

The observed energies that need to be dissipated by the PCs are

$$W^{PC1}(k) = E_5^{R2L}(k - T_2) - E_1^{R2L}(k) - W_{diss}^{PC1}(k - 1), \quad (21)$$

$$W^{PC2}(k) = E_1^{L2R}(k - T_1) - E_5^{L2R}(k) - W_{diss}^{PC2}(k - 1). \quad (22)$$

Eq. (17) also holds for Approach 2.

3.3. Analysis of drawbacks of the conventional approaches 1 and 2

As mentioned before, both methods are conservative since the reflection of energy by the energy storage element is not considered. In the following, these limitations are further analyzed in a teleoperation example.

A free motion and wall contact in this system and the respective observed energies are presented in Fig. 9. The delay was set to zero in this experiment. The potential energy of the controller as the energy storage element can be charged up from both sides (*master = Agent*

Fig. 8. Network Representation of Approach 2 and 3.

Fig. 9. Energy Behavior of a Controller with Storage Element.

$\Lambda 1$ and $slave = Agent \Lambda 2$). In this bilateral experiment with PF_{comp} architecture, the master controls the slave in free motion until the slave touches a rigid wall ($K_e \approx \infty, B_e \approx 0$) at about $t = 3.4s$. During free motion ($K_e = 0, B_e \approx 0$), the master injects the energy E_B^{L2R} into the controller (storage element) at port B in L2R direction which leaves this storage element mainly as E_C^{L2R} such that the slave is moved. Therefore, the energy storage of the controller E_{St} is almost empty during free motion ($t = [0s, 3.4s]$).

When the slave touches the wall ($t = [3.4s, 5s]$), no energy can flow on the side of the slave since its velocity is zero (constant E_C^{L2R} and E_C^{R2L}). With the wall penetration of the master, the energy storage E_{St} is filled up by energy E_B^{L2R} . When the master moves out of the contact, the energy of the storage is released as E_B^{R2L} in R2L direction to press the master out of the wall (energy reflection).

Mainly during wall contacts, or in general when the motion of one robot is hindered e.g. by obstacles, workspace limitations or high damping, energy might be reflected by the network element storing potential energy. Respecting the energetic behavior of the storage element, the state of the art approaches have the following conservatism:

- In Approach 1, the passivity controller at port B dissipates energy in L2R direction (that would otherwise charge up the energy storage element) although this energy might be reflected back in R2L direction (if the PC would be deactivated). This may lead to over conservative energy dissipation. Also, for example the force or position that is sent to the storage element from Agent $\Lambda 1$ is varied by the PC at port B. Thus, the charging of the energy storage element is lower than intended by Agent $\Lambda 1$ which can change the coupling behavior drastically, as among others position drift can appear. The effect of the port B PC on the conservatism of Approach 1 will be further analyzed in the experiments of Section 5 and the experimental comparison in Section 6.
- The energy plots $St E^{R2L}$ and $St E^{L2R}$ in Fig. 9 serve the analysis of the conservatism of Approach 2. The charging of the spring by E_B^{L2R} is considered as an energy dissipation $St E^{L2R}$ by the en-

ergy storage element in Approach 2 since no power leaves the energy storage element during the wall contact at port C (E_C^{L2R}). In contrast, the release of energy $St E^{R2L}$ to the master in R2L direction is observed as an energy generation since no power enters at port C (E_C^{R2L}) during the wall contact. This energy which is wrongly interpreted as generated energy $St E^{R2L}$ is dissipated by the PCs since the dissipation $St E^{L2R}$ happens in the other direction of energy flow and therefore does not compensate for the energy generation. Thus, the power flow direction dependent analysis of Approach 2 results in high dissipation and high conservatism. Also, the performance of Approach 2 is analyzed in detail in the experiments of Section 5.

4. Proposed method considering energy reflection

Considering the drawbacks of the conventional TDPA methods as explained in Section 3, this section proposes a less conservative method by considering the energy reflection at the potential energy storage element.

Fig. 10 visualizes the basic idea of the proposed method applied to a delayed coupled network system. The main motivation of this proposed method is that we can guarantee overall passivity without being restricted by the direction of energy flow. Therefore, we bound the output energy of the 2 port by the ideal intended amount of input energy to the energy storage element from the coupled passive system around it (terminations of the 2 port). Similar to Approach 2 in Section 3, two PCs are located at port A and port C in order to consider the energy storage element together with the CC in the delayed 2 port. Thus, the network representation of Approach 3 equals the one of Approach 2 presented in Fig. 8. However, in contrast to Approach 1 and 2, one unique available amount of energy is collected in the energy monitoring unit (battery like shape) collecting the energy input from both sides of the delayed 2 port. Since this monitoring unit has a physical relation to the energy storage element, the monitoring unit is located on the right side of the communication channel. Thus, the asymmetric setup of the physical system is represented in the proposed approach. Locating the monitoring unit on the left side of the CC does not guarantee a stable system behavior due to the loss of this physical relation and the evaluation of this relocation remains for future work. The energy monitoring unit is charged up by the dark gray (port A) and light gray arrow (port C) representing the power input in L2R and R2L direction, respectively. The energy observation at port C in this asymmetric structure guarantees the consideration of energy generation by the CC. This is described in more detail in Section 4.2. The dashed arrows indicate where the passivity controllers dissipate the excessive amount of energy considering the available energy in the monitoring unit. As explained later in more detail, the distribution of the dissipation to PC1 and PC2 depends on

Fig. 10. Proposed Energy Observation and Passivity Control Considering Energy Reflection (Approach 3).

the current distribution of output power of the energy storage element to port B and port C. Unlike the conventional TDPA, the unified energy monitoring unit allows a direction independent energy distribution respecting energy reflection.

In the following, the advantages of the proposed design and the concept of the ideal energy storage in the monitoring unit are presented in Section 4.1 and Section 4.2 respectively. The detailed implementation is described in Section 4.3.

4.1. Advantages over the conventional TDPA

In contrast to Approach 1, the energy in Approach 3 can pass at port B to the energy storage element (L2R) without being affected by a PC. Thus, the energy storage element that serves the desired coupling behavior is charged up as intended by the connected agents. This becomes clear when analyzing the analytical energy equation of the storage element: Exemplary, in the coupling through a position controller, the energy storage element equals a spring potential. This potential E_{pot} can be calculated from the stiffness K : $E_{pot}(t) = 0.5K(x_L^*(t) - x_R(t))^2$, with input x_L^* from Agent $\Lambda 1$ and x_R from Agent $\Lambda 2$. In Approach 1, the input x_L^* is delayed and varied by the PC at port B whereas in the proposed Approach 3, x_L^* is only delayed. Therefore, in contrast to Approach 1, the energy storage element is charged up as intended by Agent $\Lambda 1$ in Approach 3.

Similar to Approach 2, the energy that is generated by the CC in L2R direction and that crosses the storage element can be limited on the right side of the storage element (port C). In contrast, energy that crosses the CC in L2R direction and that is reflected by the storage element back in R2L direction is, in Approach 3, only affected by passivity control when it leaves the delayed 2 port on the left side. In Approach 1, this reflected energy is passivity controlled on the way to the energy storage (L2R) and on the way back (R2L), which might lead to higher conservatism. The proposed concept has huge advantages concerning conservatism over Approach 2, where no reflection is considered since the energy behavior of the storage element is interpreted as a direction dependent combination of energy generation and dissipation.

4.2. Ideal and real energy storage

Note that the resulting energy content of the energy monitoring unit in Approach 3 (ideal storage) is not equal to the real energy content of the energy storage element, since that is affected by energy generation in the CC. Fig. 11 explains the difference between the ideal and real energy content in more detail. Since the active element CC adds energy in L2R direction, the real storage (energy content of the energy storage element) which is filled up with the energies at Port 3 and Port 4 is equal to or higher than the ideal storage (energy content of the energy

monitoring unit). The energy monitoring unit collects the energy that is introduced from the agents into the 2 port between port 1 and 5 such that the ideal energy content can be regarded as the desired energy content of the controller (energy storage element). As depicted in Fig. 11, the ideal storage is built up by the power entering in L2R direction at port 2 (P_2^{L2R}) and in R2L direction at port 4 (P_4^{R2L}). As much energy as the ideal storage (energy monitoring unit) contains may leave at port 2 in R2L and at port 4 in L2R direction. Therefore, the allowed power output $P_2^{L2R, des}$ and $P_4^{R2L, des}$ is calculated for the two directions with a logic that is described in Section 4.3. The limitation of the output power is assured by the passivity controllers PC1 and PC2. PC2 limits the actual power output to $P_2^{L2R, des}$. The power $P_4^{R2L, des}$ is sent to the left side of the CC where $P_4^{R2L, des}$ may exit at port 2 to Agent $\Lambda 1$. Therefore, PC1 has to consider the delayed desired power output $P_4^{R2L, des}(k - T_2)$ to limit $P_2^{L2R}(k)$.

4.3. Implementation

In contrast to the approaches with direction dependent dissipation Approach 1 and Approach 2, the passivity control is split up in two parts. In the first step, a limited, desired power output $P_2^{L2R, des}(k)$ and $P_4^{R2L, des}(k)$ of the energy storage element is determined and in the second step, the delay in R2L direction is considered. Analogous to Approach 2, the 2 port passivity condition of Approach 3 is

$$E_1^{L2R}(k) + E_5^{R2L}(k) \geq E_1^{R2L}(k) + E_5^{L2R}(k). \quad (23)$$

The basic idea of the proposed concept is the consideration of the ideal energy storage $E_{St}(k)$ in the energy monitoring unit which is built up by the energies $E_2^{L2R}(k)$ and $E_4^{R2L}(k)$. As described in Section 4.2, the available amount of energy that has to be accounted in the energy monitoring unit E_{St} can be determined by

$$E_{St}(k) = E_{St}(k-1) + P_2^{L2R}(k - T_1)T_s + P_4^{R2L}(k)T_s. \quad (24)$$

It is important to note that the power $P_3^{L2R}(k)$ measured at port 3 is not considered as an input, since it is affected by delay. But, since the energies are monotonously increasing and with the 2 port passivity condition (7), it is clear that the delayed input energy from port 2 can be applied instead.

The passivity control is split into two parts: At first, the excessive amount of energy that leaves the energy storage element due to the energy generation of the CC in L2R direction, has to be determined. Later, the allowed output power $P_2^{L2R, des}(k)$ and $P_4^{R2L, des}(k)$ that may leave the energy storage element has to be calculated.

1. The power that actually leaves the energy storage element at port 3 and 4 may lead to instability since additional energy may be injected into the storage element by the CC in L2R direction. The actual output power $P_{out}^{act}(k)$ of the energy storage element in both directions of energy flow is:

$$P_{out}^{act}(k) = P_3^{R2L}(k) + P_4^{L2R}(k). \quad (25)$$

If this power is smaller than or equal to the energy content of the energy monitoring unit ($P_{out}^{act}(k)T_s \leq E_{St}(k)$), this power may leave at the respective ports since it would not violate the passivity condition. Only if more power than available is exiting at port 3 or 4, the power output of the energy storage element has to be limited. The excessive power output $P_{exc}(k)$ in both directions can be calculated as

$$P_{exc}^{R2L}(k) = \begin{cases} P_{exc}(k) \frac{P_3^{R2L}(k)}{P_{out}^{act}(k)}, & \text{if } E_{St}(k) < P_{out}^{act}(k)T_s, \\ 0, & \text{if } E_{St}(k) \geq P_{out}^{act}(k)T_s \end{cases} \quad (26)$$

$$P_{exc}^{L2R}(k) = \begin{cases} P_{exc}(k) \frac{P_4^{L2R}(k)}{P_{out}^{act}(k)}, & \text{if } E_{St}(k) < P_{out}^{act}(k)T_s, \\ 0, & \text{if } E_{St}(k) \geq P_{out}^{act}(k)T_s \end{cases} \quad (27)$$

Fig. 11. Comparison of Real and Ideal Potential Energy Storages.

with the power $P_{exc}(k)$ that has to be dissipated in the current time step:

$$P_{exc}(k) = E_{St}(k)/T_s - P_{out}^{act}(k). \quad (28)$$

Here (Eqs. (26) and (27)), the dissipation of excessive energy is distributed to $L2R$ and $R2L$ direction proportionately to the real power output $P_3^{R2L}(k)$ and $P_4^{L2R}(k)$ in the respective direction. Although other distributions are conceivable, the chosen distribution seems most reasonable since it is related to the current output power.

- The excessive power $P_{exc}^{L2R}(k)$ can be directly subtracted from the power $P_4^{L2R}(k)$ by the right hand side PC2:

$$P^{L2R,des}(k) = P_4^{L2R}(k) + P_{exc}^{L2R}(k), \quad (29)$$

$$W^{PC2}(k) = \sum_{j=0}^k (P^{L2R,des}(j) - P_4^{L2R}(j))T_s - W_{diss}^{PC2}(k-1). \quad (30)$$

The energy $W^{PC2}(k)$ is then dissipated by PC2 according to Eq. (11).

PC1 has to assure that not more power than $P^{R2L,des}(k)$ with

$$P^{R2L,des}(k) = P_3^{R2L}(k) + P_{exc}^{R2L}(k) \quad (31)$$

leaves at port 2 in $R2L$ direction. Under consideration of the energy generation of the time delay in the communication channel, the observed energy of PC1 can be calculated:

$$W^{PC1}(k) = \sum_{j=0}^{k-T_2} P^{R2L,des}(j)T_s - \sum_{j=0}^k P_2^{R2L}(j)T_s - W_{diss}^{PC1}(k-1). \quad (32)$$

This energy $W^{PC1}(k)$ is then dissipated by PC1 according to Eq. (11).

Impedance type PCs lead to forces with high frequencies due to sudden force changes. The authors of [16] proposed an additional passive virtual mass spring system to circumvent this effect. The virtual mass spring system acts as a low pass filter of force and velocity in both directions in a way that passivity is maintained.

For the next time step, the available amount of energy in the energy monitoring unit $E_{St}(k)$ has to be updated, as the powers $P_3^{R2L}(k)$ and $P_4^{L2R}(k)$ have exited at the respective ports of the energy storage element:

$$E_{St}(k) = E_{St}(k-1) + (P_2^{L2R}(k-T_1) + P_4^{R2L}(k) - P_3^{R2L}(k) - P_4^{L2R}(k))T_s. \quad (33)$$

Note that $P_3^{R2L}(k)$ needs to be considered instead of $P_2^{R2L}(k-T_2)$ due to the delay.

4.4. Passivity proof

Fig. 12 presents the 4 steps (A-D) of the passivity control approach that fulfill the passivity condition of the 2 port between port 1 and port 5. In step A of Eq. (24), the ideal reference storage is calculated that considers the input energies of the 2 port. The desired output powers are limited by the ideal storage E_{St} or the energy inputs P_2^{L2R} and P_4^{R2L} respectively

$$\sum_{j=0}^k P^{R2L,des}(j)T_s + \sum_{j=0}^k P^{L2R,des}(j)T_s \leq \sum_{j=0}^{k-T_1} P_2^{L2R}(j)T_s + \sum_{j=0}^k P_4^{R2L}(j)T_s \quad (34)$$

(compare Eqs. (26) (31)) in step B. Finally, in step C and D, the passivity controllers PC1 and PC2 assure that

Fig. 12. Steps A to D of the Passivity Control.

- $E_1^{R2L}(k) \leq \sum_{j=0}^k P^{R2L,des}(j)T_s$ and
- $E_5^{L2R}(k) \leq \sum_{j=0}^k P^{L2R,des}(j)T_s.$

Overall, assuming zero initial energy, the 2 port passivity condition (7) is fulfilled, since the outgoing energies are lower than the ingoing energies:

$$E_1^{R2L} + E_5^{L2R} \leq E^{R2L,des}(k) + E^{L2R,des}(k) \leq E_1^{L2R} + E_5^{R2L}. \quad (35)$$

Note that these energies are monotonously increasing.

5. Application to teleoperation

This section describes the application of the proposed Approach 3 to a teleoperation setup.

The following experiments serve the performance comparison of the three presented approaches. The experiments have been performed with the 1 DoF Master Slave System developed by SENSODRIVE GmbH (see Fig. 13). The control software ran on a real time system (QNX) at 1kHz sampling rate and was developed in Matlab/Simulink.

The first experiment Exp1 presents a free motion scenario without contacts at 200ms roundtrip delay with Approach 1 (see Fig. 14). The port numbers are denoted according to Fig. 5. At $t = [5s, 7s]$, it is obvious that the position synchronization is not perfect since Agent $\Lambda 2$ does not reach the maximum deflection of Agent $\Lambda 1$. This behavior results, to some extent, from the admittance type PC that causes a position drift. Note that the authors of [17,18,26] proposed different methods to compensate for the effect of position drift. Here, the concept of [17] was implemented. Still, due to the high delay, the compensation is limited.

The second experiment Exp2 in Fig. 15 shows a wall contact at 30ms roundtrip delay in a setup with Approach 2. It can be analyzed at $t = [7s, 7.5s]$ that the feedback torque to Agent $\Lambda 1$ is reduced gravely when Agent $\Lambda 1$ moves out of the wall. This results from the wrong interpretation of the energy reflection as an energy generation in Approach 2 (discussed in Section 3). In contrast to Approach 1, no position drift appears, since the PCs don't vary the input to the coupling controller in Approach 2.

The remaining experiments focus on the proposed concept (Approach 3). The system was tuned at the verge of stability at

Fig. 13. 1-DoF Master-Slave-System.

Fig. 14. Exp1: Free Motion and Wall Contact with 200ms roundtrip delay in Approach 1.

Fig. 15. Exp2: Wall Contact with 30ms Roundtrip-Delay in Approach 2.

10ms roundtrip delay (controller stiffness $K_C = 2 \frac{Nm}{rad}$, controller damping $B_C = 0.01 \frac{Nms}{rad}$). The third experiment Exp3 (see Fig. 16) presents the performance of the system by applying Approach 3 at 30ms roundtrip delay. The position following of the two devices is satisfactory. The energy plot E_{pp}

$$E_{pp}(k) = E_1^{L2R}(k) + E_5^{R2L}(k) - E_1^{R2L}(k) - E_5^{L2R}(k) \quad (36)$$

(analogous to Eq. (7)) serves as the passivity proof of the PC controlled network between port 1 and port 5 (see Fig. 8). The charging and releasing of the spring during the two wall contacts ($t = [9.3s, 10.6s]$ and $t = [12.7s, 13.2s]$) are clearly visible in the energy plot. Since E_{pp} is never negative, the passivity during the operation is confirmed. There is only little PC dissipation during free motion. When the master moves the slave against the wall ($t = [9.3s, 10.1s]$), the storage is built up such that no power has to be dissipated since it is stored in the energy storage element. When the master moves out of the wall ($t = [10.1s, 10.7s]$), power is flowing to the master such that mainly PC1 dissipates energy that was generated by the communication channel. Since the slave is steady during a contact with a rigid wall, no power flows to the slave. Especially when the master moves out of the wall, the dissipation is much lower in Approach 3 compared to Approach 2 in Exp2. This can be analyzed

Fig. 16. Exp3: Wall Contact with 30ms Roundtrip-Delay in Approach 3.

Fig. 17. Exp4: Free Motion and Wall Contact with 400ms Roundtrip-Delay in Approach 3.

in the force feedback to the master which is more gravely reduced in Approach 2 ($t = [7.2s, 7.5s]$).

The fourth experiment Exp4 presents a free motion situation with slow ($t = [1s, 3.5s]$) and fast motion ($t = [3.5s, 6.5s]$) and a wall contact of the slave ($t = [12.5s, 15.5s]$) at 400ms roundtrip delay (see Fig. 17). The position following is clearly affected by the high delay. The energy plot E_{pp} is always positive and thus confirms the passivity of the PC controlled network. Mainly passivity controller PC1 is active during the wall contact. Very little energy needs to be dissipated in free motion at low velocities. In contrast to Approach 1 (Exp1), no position drift appears despite the high communication delay due to the consideration of energy reflection and the application of impedance type PCs.

Fig. 18. Experimental Setup of Comparison Study.

6. Experimental comparison study

In this section, the time delay control method of [17] (Approach 1) and the proposed concept (Approach 3) are compared in a PF_{comp} architecture with respect to different performance measures at varying delays. The analysis in Section 3.3 and especially the experiment in Fig. 15 show that Approach 2 has clear logical disadvantages over Approach 3 and is therefore excluded from the comparison.

Different metrics have been proposed to evaluate the performance of haptic devices and control approaches. For comparative studies, different performance indexes have been applied in [27,28]. The Z width and the M width were analyzed in [29] and [30] respectively. [31], [32] and [33] present performance evaluations of haptic interfaces and the respective control methods. The performance of common bilateral teleoperation concepts has been investigated in [34], [35], [36] and [37].

Here, similar to [38] that investigated the free space and stiffness transparency separately, free motion and wall contact scenarios are considered. Analogous to [15], the position error and the transmitted impedance are considered as performance measures.

6.1. Experimental setup

Two 1 DoF master slave systems have been applied as agent devices due to their low mass and low friction. To assure the reproducibility of the results and consistent system inputs, a human operator has been simulated with an additional 1 DoF system connected with the Agent A1 device through a rigid bar as presented in Fig. 18. In both approaches, a PF_{comp} architecture was used. Since the research of [17,18,26] showed that position drift compensation can improve the performance of Approach 1, the position drift compensation presented in [17] was applied to Approach 1. This setup allowed the measurement of interaction forces at Agent A1 and A2.

6.2. Method

A position controller ($K_{C2} = 2.3 \frac{Nm}{rad}$, $B_{C2} = 0 \frac{Nms}{rad}$, $B_{HO} = 0.05 \frac{Nms}{rad}$) acted on the device which replaced the human operator aiming at a sinusoidal motion with increasing frequency $f \in [0.2, 1.4]$. A maximum frequency of 1.4Hz has been chosen since a human operator should not move faster at high roundtrip delays to achieve a sufficient performance. The approaches were analyzed for different roundtrip delays ($T_i \in \{30ms, 100ms, 200ms, 400ms\}$). The stiffness K_C of the position controller connecting Agent A1 and Agent A2 was set to $K_C = 2 \frac{Nm}{rad}$ in

both approaches. This stiffness was chosen such that sufficient performance was guaranteed up to 400ms roundtrip delay. For the sake of comparability K_C was constant throughout the comparative study. Individual position controller damping B_C and local damping gains B_{A1} and B_{A2} of the devices were adapted for each roundtrip delay and approach, to achieve (subjectively rated) the best performance regarding the specific roundtrip delay. Although the Time Domain Passivity controlled system is stable for any damping, the performance can be improved applying delay dependent damping values. Note that a local damping loop at the devices can be designed as an additional passive 2 port subsystem in the network such that it can be introduced into the presented control loops without violation of the passivity criterion. To consider different environmental impedances Z_e , the approaches were evaluated in a free motion ($Z_e = 0$) and a wall contact situation with fixed Agent A2 device ($Z_e \approx \infty$).

The metrics include the features denoted in Table 1. In the wall contact experiments, high effective stiffness values $MV(K_{eff})$ are desired. In contrast, for free motion without environment contact, $MV(K_{eff})$ should be zero. The position and path error should be low in both situations. The percentage of transmitted energy (RAT_E) and the percentage of Agent A2 forces ($MV(RAT_F)$) should be close to one. In the wall contact scenario, the Agent A2 does not move such that $MV(RAT_F)$ is considered instead of RAT_E . The path $Path_{A1}$ of Agent A1 has to be analyzed in context with the interaction force F_{A2} and the effective stiffness K_{eff} . The dissipated energy E_{diss} should be low.

6.3. Results

Figs. 19 to 22 depict the results for different environmental impedances and roundtrip delays at different frequencies. Since, in general, the system performance at high delays is better at low frequency motions, the results of different frequency bandwidths are depicted.

In Fig. 19 (Exp5a), the free motion scenario at low input frequencies is depicted. At a roundtrip delay of 30ms, the dissipated energy and the

Fig. 19. Exp5a: Free Motion at $f = 0.2 Hz$.

Table 1
Metrics.

$MV(K_{eff})$	mean effective impedance of evaluated frequencies $f \in [0.2Hz, 1.4Hz]$ [15]
$Path_{error}$	path error between the path length of the human operator motion and the motion of the Agent A2 device
$Path_{A1}$	path $Path_{A1}$ of the Agent A1 device
$MV(P_{err})$	mean position error between the Agent A2 device and the delayed Agent A1 device position
$MV(F_{A2})$	mean value of the absolute measured interaction forces of Agent A2
E_{diss}	sum of energy dissipated by the two passivity controllers PC1 and PC2
RAT_E	the ratio $RAT_E = (E_{A1} + E_{A2}) / (E_{A1}^K + E_{A2}^K)$ of actual $E_{Ai}(k) = \sum_{n=0}^k (v_{Ai}(n)F_{Ai}(n))$ ($i \in \{1, 2\}$) and expected energy flow $E_{Ai}^K = \sum_{n=0}^k (v_{Ai}(n)(x_{A2}(n) - x_{A1}(n))K_C)$
$MV(RAT_F)$	the mean value of the ratio $RAT_F = (F_{A1} + F_{A2}) / 2F^K$ of actual F_{Ai} and expected computed force $F^K = (x_{A2}(k) - x_{A1}(k))K_C$

Fig. 20. Exp5b: Wall Contact at $f = 0.2Hz$.

Fig. 21. Exp6a: Free Motion at $f \in [0.2Hz - 1.4Hz]$.

position and path errors are lower for Approach 3. With increasing delay, Approach 3 dissipates relatively more energy than Approach 1 but the position and path errors increase intensively in Approach 1 despite the slow motion. The big path error of Approach 1 results from position drift and reduces transparency strongly. Aside from the 200ms condition, the effective stiffness is low in both approaches. The comparably high $MV(K_{eff})$ of Approach 3 at 200ms roundtrip delay may result from delay and frequency depending reflections in the communication channel. Note that this difference at 200ms roundtrip delay vanishes when a wider range of frequencies is analyzed (Exp6a). RAT_E has better values for Approach 3 at all delays.

In the wall contact situation at slow motion (see Fig. 20, Exp5b), the $MV(K_{eff})$ is higher for Approach 3. Also, the metric $MV(F_{A2})$ indicates that the desired Agent A2 motion results in higher Agent A2 forces in Approach 3. The position drift of the admittance type PC in Approach 1 leads to a lower wall penetration of Agent A1 (although the path of the Agent A1 device is same for both approaches) and thus to lower interaction and coupling forces. Due to lower coupling forces, the dissipated energy is reduced in Approach 1. $MV(RAT_F)$ has better values for Approach 3 at all delays.

The results at a bigger range of input frequencies in Fig. 21 (Exp6a) and Fig. 22 (Exp6b) are similar but less pronounced. Furthermore, the position and path errors increase for both approaches due to faster motions. Note that the path of Agent A1 in the wall contact situation re-

Fig. 22. Exp6b: Wall Contact at $f \in [0.2Hz - 1.4Hz]$.

Table 2
Results.

Frequency $f = 0.2Hz$

Free Motion

lower position and path errors for Approach 3
lower dissipation for Approach 3 at 30ms roundtrip-delay
higher dissipation for Approach 3 at 200ms and 400ms roundtrip-delay
low effective stiffness in Approach 1 and 3 (despite 200ms roundtrip-delay)
higher RAT_E for Approach 3

Wall Contact

higher effective stiffness for Approach 3
higher Agent A2 interaction forces of Approach 3
higher dissipation for Approach 3 at 200ms and 400ms roundtrip-delay
higher $MV(RAT_F)$ for Approach 3

Frequencies $f \in [0.2Hz - 1.4Hz]$

Free Motion

lower position and path errors for Approach 3
lower dissipation for Approach 3 at 30ms roundtrip-delay
higher dissipation for Approach 3 at 200ms and 400ms roundtrip-delay
higher effective stiffness in Approach 3 at 400ms roundtrip-delay
higher RAT_E for Approach 3

Wall Contact

higher effective stiffness for Approach 3
higher Agent A2 interaction forces of Approach 3
higher dissipation for Approach 3
higher $MV(RAT_F)$ for Approach 3

duces with the delay since the maximum frequency was set to 1.2Hz for 100ms roundtrip delay and to 1Hz for 200ms and 400ms roundtrip delay. During free motion, the effective stiffness is lower for Approach 1 but this may result from position drift and can therefore not be considered as a benefit of Approach 1. Since the motion frequency is too high for the high roundtrip delays, during wall contact, the effective stiffness is lower than at 0.2Hz motions in both approaches.

The main results are summarized in Table 2.

6.4. Discussion

In free motion, the position following is the most relevant criterion. The effective stiffness criterion provides lower accuracy in the free motion compared to the wall contact situation. Thus, considering free motion, Approach 3 with lower position and path errors promises better performance. At low roundtrip delay and slow motion, Approach 3 dissipates less energy than Approach 1. The dissipated energy is not a suitable criterion since the energy amount of the system depends on the system behavior which differs strongly for the two approaches. Due to

the position drift in Approach 1, the forces are lower. Lower forces inevitably lead to lower power flow in the system and thus to less dissipation by the passivity controllers. Also, the relative dissipation of energy is not a reliable criterion. In contrast, the percentage of transmitted energy which refers to the expected power flow resulting from the reference position and the controller constant K_C is more reasonable. Also during wall contacts, Approach 3 provides better performance. This fact can be drawn from the higher effective stiffness and higher *Agent* Λ_2 interaction forces (compare $MV(RAT_F)$ and $MV(|F_{\Lambda_2}|)$) throughout all experiments with wall contact.

At motion inputs of higher frequencies ($f \in [0.2\text{Hz} - 1.4\text{Hz}]$), the performance of both approaches decreases since the automated frequency inputs do not react on the system behavior. In teleoperation setups, a human operator is able to adapt the velocity at high communication delays. To avoid large position drift in Approach 1 and to avoid high resistive forces due to position deviations in Approach 3, with increasing delays, slower motions are required.

7. Conclusion

In this paper, a new time domain passivity control approach has been proposed that considers, in contrast to former approaches, energy reflection by an energy storage element. Thus, negative effects such as position drift or excessive energy dissipation of former approaches could be avoided. Therefore, the proposed concept considers, in addition to the energy behavior of the communication channel, the potential energy of the coupling controller as an energy storage. Experiments showed good position synchronization of two coupled agents despite a round trip delay of 400ms. These results were strengthened in a comparison with a state of the art time domain passivity control approach considering different performance metrics. The proposed approach showed better results considering position synchronization during free motion and transmitted impedances during wall contact at a wide range of communication delays. For future work, the proposed concept should also be integrated in a Position Position architecture or a 4 Channel framework and applied in more complex robotic applications.

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