A peer-to-peer Trilateral Passivity Control for delayed collaborative Teleoperation

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Abstract. In this paper a trilateral Multi-Master-Single-Slave-System with control authority allocation between two human operators is proposed. The authority coefficient permits to slide the dominant role between the operators. They can simultaneously execute a task in a collaborative way or a trainee might haptically only observe the task, while an expert is in full control. The master devices are connected with each other and the slave robot peer to peer without a central processing unit in a equitable way. The system design is general in that it allows delayed communication and different coupling causalities between masters and slave, which can be located far from each other. The Time Domain Passivity Control Approach guarantees passivity of the network in the presence of communication delays. The methods presented are sustained with simulations and experiments using different authority coefficients.

1 INTRODUCTION

Bilateral Teleoperation, where a human operator controls a remote robotic manipulator through a master device originates in the 1940's. The human thereby gained access to distant evironments or to environments behind a barrier, like the human body in minimally invasive surgery. That can also be performed over long distances as demonstrated in 2002 with the ZEUS robotic system [1]. Even though the operating surgeon was in New York, while the patient was in Strassbourg, there was still a surgeon located with the patient in case of an emergency. In the future the local surgeon could also be integrated into the teleoperation system with a local master console, enhancing the bilateral system to a trilateral system. Analogous to surgery, potential applications for trilateral systems can be found in deep see or in space, where a specialist on the ground can assist an astronout operating a robot outside a space station.

A trilateral system could either be used in a collaborative way where a local professional gets temporary support by a distanced specialist or as a training system where a trainee learns from a mentor ([2–5]). In the beginning of such a training the trainee can observe the mentor's action haptically without influence on the slave robot. Corresponding to the increase of experience the authority should be shared between the human operators (see Fig. 1) providing the trainee with progressively higher control. This procedure is in this paper solved by the variation of an authority factor.

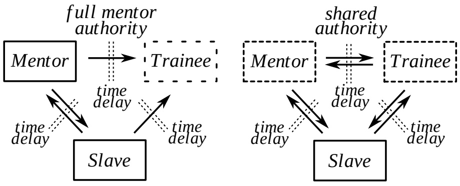


Fig. 1. Trilateral teleoperation including authority allocation and time delay

In [2] a system with authority allocation and a unilaterally controlled slave is proposed. Visual feedback of the slave's position was provided and time delay in the operators' haptic channel was considered. This system was enhanced to a peer-to-peer system in [3] with threee equally privileged peers (slave and master devices) in a four channel control architecture (4CH). However the effect of time delay was neglected here. In bilateral systems the time delay as the general challenge in remote control has been tackled with several energy based techniques i.e. the Time Domain Passivity Control Approach (TDPA, [6–8]), Raisbeck's passivity criterion [9] and the wave variables technique [10] which is closely related to the scattering formulation [11]. Besides H_∞-control [2], wave variables [4] have been utilised in multi-agent-systems to handle the effects of time delay. Llewellyn's absolute stability criterion which is less conservative than Raisbeck's passivity criterion can not be extended to a trilateral system. Furthermore those two approaches require models of the system's complex mechanical devices. The first trilateral peer-to-peer system respecting time delay is presented in this work whereby the TDPA is applied because of its two major advantages, i.e. the consideration of the ideal case assuming the time delay to be zero ($T_{delay} = 0$) in the design process and the ability to handle non-linearities and unmodeled effects [12].
The focus in this paper is placed (a) on the mechanism to distribute the authority, (b) on how to guarantee passivity in case one or more of the agents are remotely located from the others and (c) how this structure can be generalized. In section 2.1, the signal flow architecture will be discussed with focus on the authority allocation (AA). The network representation and the principles of analogy are introduced in section 2.2. The activity analysis of the authority allocation is provided in section 3. Based on this the peer-to-peer TDPA is designed and the passivity proof accomplished. Experiments are presented in section 4. Conclusions and future research will be discussed in section 5.

2 SYSTEM DESCRIPTION

2.1 SIGNAL FLOW DIAGRAM

Figure 2 shows the signal flow diagram of the proposed peer-to-peer telepresence system. In the depicted position force architecture (PF) velocity (v) and force (F) signals are exchanged between the haptic devices ($Master_1$, $Master_2$) and the robot ($Slave$) through the communication channels represented by time delay elements $e^{-T_i s}$. The PI-controllers (PI-$Ctrl$, virtual damper and spring) are corresponding to the PF architecture located on the slave's side of the communication channels (respectively for the operators' channel on the trainee's side). The factors β_{ME} and β_{TR}, corresponding to mentor and trainee respectively, determine the allocation of authority between the operators through scaling of the delayed forces from the PI-controllers. Those forces correspond to the influence of an agent on the addressed device. The relationship between the two authority variables β_{TR} and β_{ME} is given by:

$$\beta_{TR} = 1 - \beta_{ME} \quad \text{with} \quad \beta_{TR/ME} \in \{0...1\} \tag{1}$$

indicating that a reduction of the mentor's authority β_{ME} leads to a correlated increase of the trainee's authority β_{TR}. Reducing β_{ME} from 1 to 0 progressively assigns consequently higher influence on the system to the trainee. In contrast to [3] the slave's feedback signals (F_{12}, F_{13}) remain unaffected by $\beta_{ME/TR}$ since the slave's position (represented by the feedbacked force) as the main concern should always be presented correctly to the master devices.

2.2 NETWORK MODELLING

In this chapter the signal flow of the telepresence system will be transferred into network representation. This electrical modeling provides several useful tools which have been developed for circuit analysis. Concerning the energy based stability analysis the

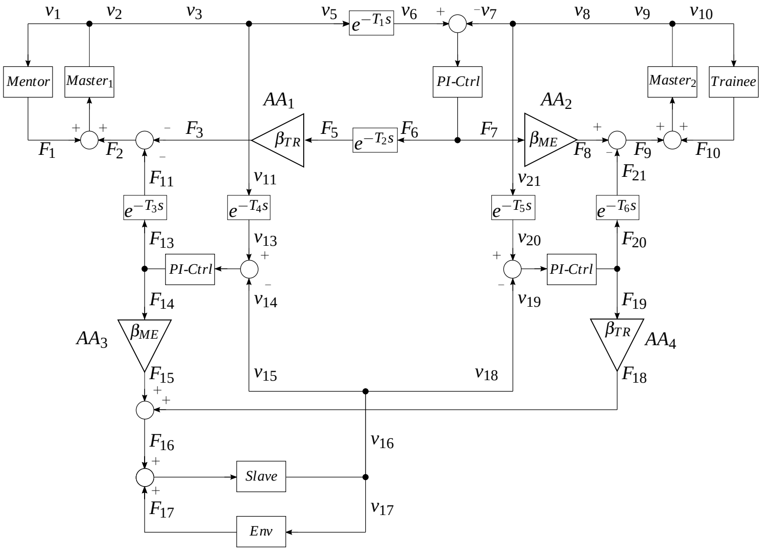


Fig. 2. Signal flow diagram of trilateral PF architecture with authority allocation (β_{TR}, β_{ME}) and time delay ($e^{-T_i s}$)

power conjugation of the network port signals presents the main advantage of this representation. Because of the analogy between the potentials force (F) and voltage and the flows velocity (v) and current the signal flow subsystems can be replaced by so-called network ports. The TDPA utilises passivity observers (PO) which compute the energies at the ports i of a network subsystem in order to analyse the system's activity behaviour:

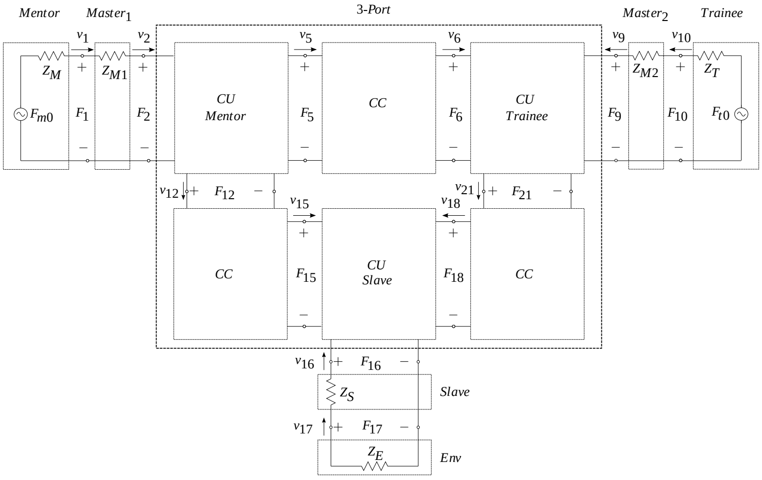


Fig. 3. General electrical analogous network representation of the trilateral system, control unit CU, communication channel CC

$$E_i(t) = \int_0^t P_i(\tau)\, d\tau,$$

where $P_i(t)$ is the power computed as:

$$P_i(t) = v_i(t)F_i(t).$$

As depicted in Fig. 4 v_i is the velocity flowing through a port i across which the force F_i is applied. The following convention regarding the signs of the port signals is assumed: If the integrated dual product $E_i(t)$ of a current entering the network and a positive voltage defined at the first terminal of the port w.r.t. the second one, is positive, the network is passive. Else, if it is negative, it is active. That means that energy flowing into the network results in positive energy. Regarding the sign of the power $P_i(t)$, the direction of flow can be computed as:

$$P_{i,in,NP}(t) = \begin{cases} P_i(t), \text{ if } P_i(t) > 0 \\ 0, \quad \text{if } P_i(t) \leq 0 \end{cases} \tag{2}$$

$$P_{i,out,NP}(t) = \begin{cases} 0, \quad \text{if } P_i(t) > 0 \\ -P_i(t), \text{ if } P_i(t) \leq 0. \end{cases} \tag{3}$$

The power $P_{i,in,NP}(t)$ flows into a regareded network subsystem at port i on the side of the network subsystem NP. Whereas $P_{i,out,NP}(t)$ stands for the power flowing out of a network subsystem at port i on the side of NP. NP are here the network subsystems terminating the 3-port such that NP can be ”M” for Mentor, ”T” for Trainee or ”S” for Slave. The energy $E_i(t)$ and the power $P_i(t)$ are positive defined and monotone (see eq. (2) and (3)). The passivity controllers (PC) dissipate the amount of energy undesirably generated in an observed network. The subsystem terminated by the devices $Master_1$, $Master_2$ and the $Slave$ robot can be identified as a 3-Port (see Fig. 3), which can be split up in a modular way into three communication channel networks (CC) and three control unit networks (CU). The CUs include the authority allocation (eq. (1)), force distribution and the PI-controllers j ($Z_{PI_j}(s) = K_p/s + K_v$). Depending on the control architecture, different control unit and communication channel blocks can be inserted. In Fig. 5, the CC for a position force (PF) architecture is depicted examplifying the communication between mentor and trainee. The force transmission over the PF communication channel to the mentor can be represented as a voltage source whereas the velocity transmission to the trainee corresponds to a current source [14]. For the study case, i.e. the PF architecture, the network blocks of the mentor and trainee control units are illustrated in Fig. 6. The controllers are represented by an impedance Z_{PI_j}.

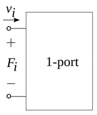


Fig. 4. 1-port network with port i, velocity v_i and force F_i

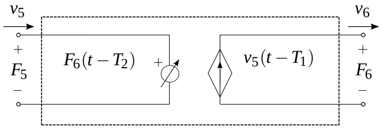


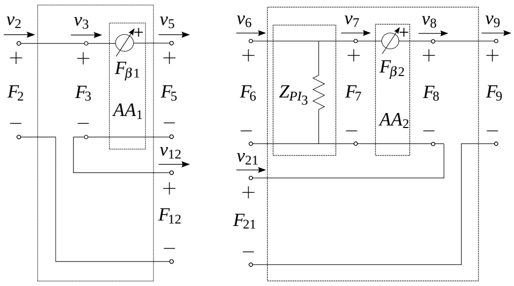
Fig. 5. Network representation of communication channel CC for PF architecture

2.3 AUTHORITY ALLOCATION

The next element which needs to be represented in the electrical scheme is the authority allocation (AA) governed by the coefficients β_{TR} and β_{ME}, as defined in (1). Since the velocities of each device (masters and slave) are not scaled by the authority coefficient ($v_3 = v_5$, $v_7 = v_8$) the AA can be modeled as a dependent force source (see Fig. 7(b)) whose value is given by:

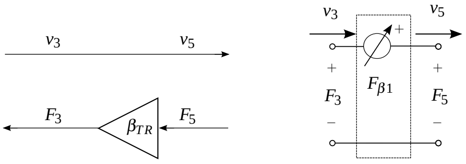
$$F_{\beta 1} = F_5 - F_3 = (1 - \beta_{TR})F_5. \tag{4}$$

The force $F_{\beta 1}$ corresponds to the force which is substracted from F_5 through the scaling of the AA.



(a) Mentor's side (b) Trainee's side

Fig. 6. Network representation of control unit CU for PF architecture



(a) Signal flow diagram (b) Network representation

Fig. 7. Authority allocation analogy for AA_1

2.4 FORCE DISTRIBUTION

The force distribution can be understood by checking the interconnection of the CU's. Taking for instance the trainee side (see Fig. 6(b)) the port 9 attached to the device $master_2$ is the result of a series interconnection of port 8 of the authority allocation AA_2 and port 21 next to the CC between trainee and slave.

Thus, the resulting force is given by the sum of each interconnected network. For the case of $master_1$, Fig. 6(a), the sum is given by $F_2 = F_3 + F_{12}$. To verify that the interfaces between the blocks surrounding the force distribution block satisfy the port requirement, it has to be shown that the in- and outflowing velocities at each port are identical. This requirement is fulfilled as can be seen by looking at Fig. 8: $v_2 = v_3 = v_{12}$.

3 PASSIVE TRILATERAL CONTROL

To examine the influence of the CU on the TDPA design the energy behaviour of force distribution and authority allocation has to be studied.

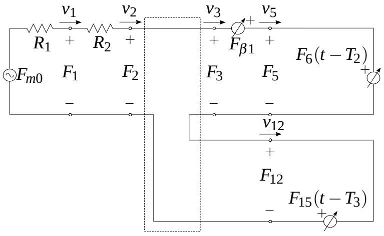


Fig. 8. The mentor's electrical circuit in the PF architecture

3.1 ENERGY ANALYSIS OF SUBSYSTEMS

As easily can be analysed in Fig. 8 the force distribution is a lossless element, since it is designed as a series connection containing no network elements. It follows from the definition of the authority allocation (4) that e.g. AA_1 (see Fig. 7(b)) purely injects or dissipates energy depending on the direction of energy flow. AA_1 affects in trainee direction the power $P_{3,in,M}$ and in mentor direction the power $P_{5,in,T}$ ($v_5 = v_3$):

$$
\begin{aligned}
P_{5,out,T}(t) &= P_{3,in,M}(t) + P_{AA_1,M} \\
P_{3,out,M}(t) &= P_{5,in,T}(t) + P_{AA_1,T} \,.
\end{aligned}
$$

Where $P_{AA_1,NP}(t)$ is the positive defined power flowing towards trainee ($NP = M$) and mentor ($NP = T$) respectively. The corresponding energies $A_{S,NP}$ (the energy is injected by network subsystem S from the direction of NP) can be computed as:

$$
A_{AA_1,M}(t) = \int_0^t P^{act}_{AA_1,M}(\tau)\, d\tau \quad \text{with} \tag{5}
$$

$$
P^{act}_{AA_1,M}(t) = \begin{cases} -(P_{3,in,M}(t) - P_{5,out,T}(t)), & \text{if } P_{3,in,M}(t) - P_{5,out,T}(t) \leq 0 \\ 0, & \text{if } P_{3,in,M}(t) - P_{5,out,T}(t) > 0. \end{cases} \tag{6}
$$

The power $P^{act}_{AA_1,M}(t)$ accounts in contrast to $P_{AA_1,M}(t)$ only power generated by AA_1 (for the case of the authority allocation $P^{act}_{AA_i,M}(t)$ equals $P_{AA_i,M}(t)$). The positive defined absolut energy dissipation $D_{AA_1,M}(t)$ of a subsystem can be evaluated analogously:

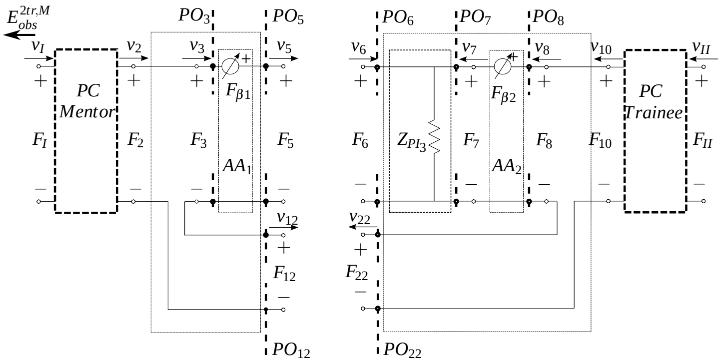
$$
D_{AA_1,M}(t) = \int_0^t P^{dis}_{AA_1,M}(\tau)\, d\tau \quad \text{with} \tag{7}
$$

$$
P^{dis}_{AA_1,M}(t) = \begin{cases} P_{3,in,M}(t) - P_{5,out,T}(t), & \text{if } P_{3,in,M}(t) - P_{5,out,T}(t) > 0 \\ 0, & \text{if } P_{3,in,M}(t) - P_{5,out,T}(t) \leq 0. \end{cases} \tag{8}
$$

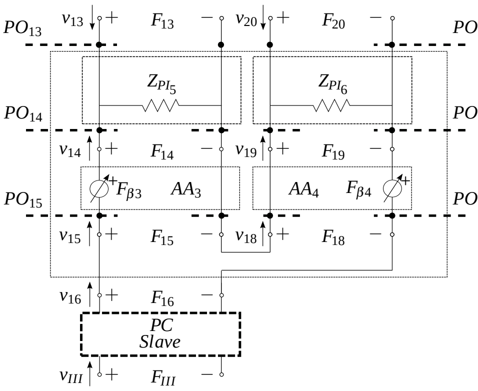
The power $P^{dis}_{AA_1,M}(t)$ accounts analogously to $P^{act}_{AA_1,M}(t)$ only power dissipated by AA_1. AA_1 shows active behaviour in direction of the trainee since the at port 5 outflowing power is always higher than the at port 3 inflowing one. Thus e.g. $D_{AA_1,M}(t)$, $D_{AA_2,T}(t)$ and also $A_{AA_1,T}(t)$ and $A_{AA_2,M}(t)$ are always zero. In contrast energy is e.g. by AA_1 in direction of the mentor and by AA_2 in direction of the trainee ($D_{AA_1,M}(t)$, $D_{AA_2,T}(t)$) partly dissipated. The activated energy must not be dissipated by the TDPA to serve the functionality of the authority allocation.

3.2 PLACEMENT OF PASSIVITY OBSERVERS AND CONTROLLERS

For the proposed peer-to-peer system three passivity observer (PO) and passivity controller (PC, [6]) placements have been studied. Each of those placements focuses mainly the passivation of the communication channels. The handling of the 3-port as a black-box surrounded by POs and PCs corresponding to the TDPA controlled 2-Port in the bilateral system is not possible, since the generated and dissipated energy in the system has to be differentiated by its direction of flow [7].



(a) Mentor's side (b) Trainee's side



(c) Slave's side

Fig. 9. PO/PC system and control units for PF architecture

Channel-PO/PC: One possible placement corresponds to the standard bilateral PO/PC system which encloses only the communication channel. Thus in the channel-PO/PC placement one PO/PC system is applied on each of the three CCs in the trilateral system. In contrast to the approach proposed in the following this placement can also be implemented using the wave variables technique.

Track-PO/PC: As already suggested in [13] a bilateral network (track) surrounded by the PO/PC system can include an I-controller (the integral component acts on the position) besides the CC. In the track-PO/PC placement of the trilateral system the authority allocation is added to the TDPA controlled track in addition to the communication channel and the corresponding controllers (track: AA, CC, PI). Thus at each port of the 3-Port one impedance PC is sufficient to dissipate the energy generated in the two tracks in direction to the corresponding device. In Fig. 9 the PO/PC system for the track-PO/PC is depicted. The POs enclose each authority allocation, PI-controller and communication channel. This is the most general approach since it can be applied for all types of control architectures. In this approach the activity of the AAs must be observed and allowed by the PC. Stability is guaranteed e.g. by the Routh-Hurwitz criterion under neglection of the time delay. Furthermore the dissipation of the track subsystems have to be taken into account since they would obscure the activity of other subsystems. Besides the authority allocation each PI-controller j and especially its proportional part as a damper dissipates the energy $D_{PI_j,NP}(t)$ which is calculated analogously to (8). In contrast to the channel-POPC this activity is dissipated by the PCs which leads to a more conservative but also more robust system. On the other hand the track-PO/PC enables the conjoint passivation of two tracks leading to one 3-Port termination. Thus not the whole energy generated by an active CC in one track has to be dissipated by the corresponding PC if the CC of the other track is dissipating energy at the same time.

3.3 PASSIVITY PROOF

In this section the mentor's track-PO/PC system will be examined representatively. PO_8 and PO_{15} observe the positive energy flowing into the tracks. PO_7 observes with PO_8 the energy injection of AA_2 and with PO_6 the disspation of PI_3 in the direction of the mentor. This holds for PO_{13}, PO_{14} and PO_{15}, AA_3 and PI_5 in the same way. The dissipation of AA_1 is observed by PO_5 and PO_3. PO_3 and PO_{12} measure the energy exiting to the mentor. The requirement for passivity of a m-port

$$\begin{aligned} E_{obs}^{mPort}(t) = \int_0^t & F_1(\tau)v_1(\tau) + F_2(\tau)v_2(\tau) + \\ & + F_m(\tau)v_m(\tau)\,d\tau + E(0) \geq 0. \end{aligned} \tag{9}$$

implies that the amount of energy flowing into the system is higher than the one of the outflowing. The energy $E(0)$ which is stored in the system at $t = 0$ has to be respected. To prove that the mentor's track-PO/PC passivates the communication channels, the energy $E_x^{2tr,M}(t)$ and the energy $E_{obs}^{2tr,M}(t)$ have to be regarded. $E_x^{2tr,M}(t)$ is the energy exiting the tracks at port I (see 9(a)) to $master_1$ in a passive system. In a active system the energy $E_{obs}^{2tr,M}(t)$ exits at Port I after dissipation of energy (generated by the tracks) through the PC. The passivity of the tracks is secured if the energy compassed by the PC functionality $E_{obs}^{2tr,M}(t)$ is smaller than $E_x^{2tr,M}(t)$:

$$E_x^{2tr,M}(t) - E_{obs}^{2tr,M}(t) > 0. \tag{10}$$

The delay-free energy $E_x^{2tr,M}$ which guarantees the passivity of the tracks is given by:

$$\begin{aligned} E_x^{2tr,M}(t) = {} & E_{8,in,T}(t) + A_{AA_2,T}(t) - D_{AA_1,T}(t) - D_{PI_3,T}(t) + \\ & + E_{17,in,S}(t) + A_{AA_3,T}(t) - D_{PI_5,S}(t) - E_{2,out,M}(t). \end{aligned}$$

The in section 3.1 presented calculation of energy generation and dissipation serves the observation of the absolute by a subsystem generated or dissipated energy respectively. If instead of the in- and outflowing power flows the in- and outflowing energies are regarded (as in the follwoing for the communication channel) the overall energy behaviour is measured. These differing calculation make no difference for the AA_i since these network ports have a constant behaviour in each direction of flow. In contrast for the PI-controllers an absolute activity calculation (using powers) is necessary since they are at different instants highly dissipating and generating energy. Regarding the overall energy behaviour would lead to an energy storage in the PO/PC system. The PC would then react firstly on track activity when the storage is discharged which would result in instability.

The energy $E_{obs}^{2tr,M}(t)$ (observing the activity of CC_2, CC_4, PI_3 and PI_5) is given by:

$$\begin{aligned}E_{obs}^{2tr,M}(t) = {} & E_{8,in,T}(t-T_2) + A_{AA_2,T}(t-T_2) - D_{AA_1,T}(t) - D_{PI_3,T}(t-T_2) + \\ & + E_{17,in,S}(t-T_3) + A_{AA_3,T}(t-T_3) - D_{PI_5,S}(t-T_3) - E_{2,out,M}(t).\end{aligned}$$

The PO/PC system designed by this $E_{obs}^{2tr,M}(t)$ leads to the dissipation of the communication channels' and the PI-controllers' activities $A_{PI_j,NP}(t)$. To fulfill (10) in terms of passivity the following inequality must hold:

$$E(t-T_{2/3}) - E(t) < 0.$$

Since the in- and outflowing energies E_{in}, E_{out}, activities A_{AA} and the dissipations D_{AA} and D_{PI} are defined to be purely increasing, never decreasing ($E(t) > E(t-T_{2/3})$) inequality (10) and thus the passivity can be proven. The energy $E_{2diss}^{2tr,M}$ which has to be dissipated by the mentor's PC in the time step T_S results in

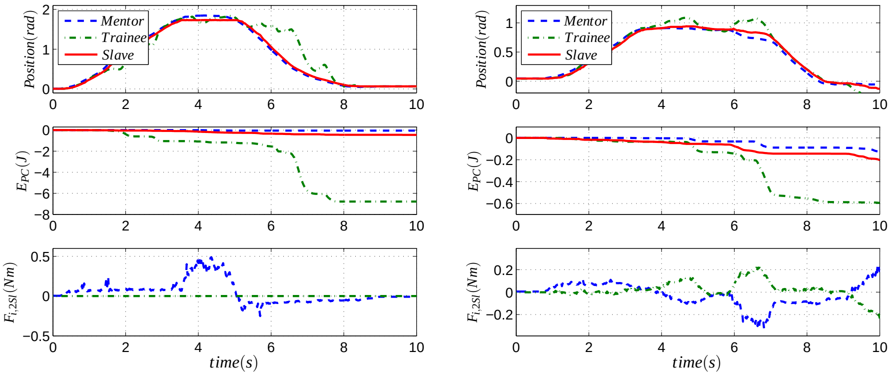
$$\begin{aligned}E_{2diss}^{2tr,M}(t) = {} & E_{8,in,T}(t-T_2) + A_{AA_2,T}(t-T_2) - D_{AA_1,T}(t) - D_{PI_3,T}(t-T_2) + \\ & + E_{17,in,S}(t-T_3) + A_{AA_3,T}(t-T_3) - D_{PI_5,S}(t-T_3) - E_{2,out,M}(t) \\ & - E_{diss}^{2tr,M}(t-T_S)\end{aligned}$$

The energy $E_{diss}^{2tr,M}(t-T_S)$ is taken into account which has been dissipated by the mentor PC until the current time step T_S. The passivity proof and PO/PC design of trainee and slave PC is analogous.

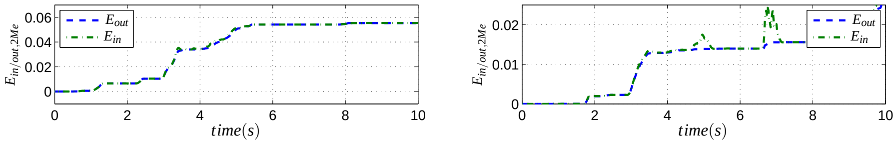
4 EXPERIMENTS

In this section experiments analysing the system's performance in dependence of time delay and authority allocation will be presented. In the following the track-PO/PC has been applied in combination with a position force architecture (PF) on rotatory 1DoF haptic devices (by SensoDrive) which were connected to a QNX system. This hardware was chosen for the masters and the slave likewise. For the experiments every communication channel has been restrained by one unique time delay.The PF control architecture has been implemented on Matlab/Simulink. Compiling the model by Real-Time Workshop supported appropriately real-time performance on a QNX machine.

The system has been tuned to go unstable with $T_i = 10ms$ (unique PI parameters: damping $B_{PI} = 0.06\frac{Nms}{rad}$, stiffness $K_{PI} = 3.5\frac{Nm}{rad}$).
In the first experiment (see figure 10(a), 10(c)) the mentor has the full authority ($\beta_{ME} = 1$). The mentor guides the slave against a wall (time: $3.5s$ to $5s$) marginally penetrating it. The position plot shows that the slave follows the mentor very well. The trainee though resists the movement. During this resistance the trainee's PC dissipates a high amount of energy (E_{PC}). The effect of the authority allocation can be recognized looking at plot $F_{i,2Sl}$ (see 10(a)). $F_{18,2Sl}$ is the force sent to the slave from the trainee side. This force is completely canceled by the AA ($\beta_{TR} = 0$) whereas the mentor's force $F_{15,2Sl}$ is entirely received by the slave. The passivity proof is accomplished in 10(c) where it can be seen that E_{out} is always smaller than E_{in}.With $\beta_{ME} = 0.75$ the trainee is assigned a little control in the second experiment as the forces $F_{i,2Sl}$ confirm (10(b)). The position following can be analysed in phases of consistent operator movement and is satisfactory despite the delay of 50ms. The position diagram in figure 10(b) shows that the slave does not stick as much to the mentor as in the first experiment since it is also influenced by the triainee's movement. The passivity proof plot (see 10(d)) shows that the mentor's PC dissipates too much energy in phases of reconvergence of the three device.



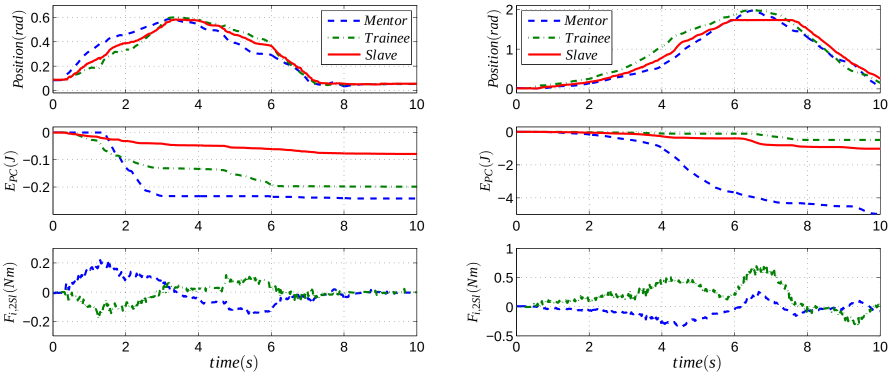
(a) Performance ($\beta_{ME} = 1$, $T_i = 50ms$) (b) Performance ($\beta_{ME} = 0.75$, $T_i = 50ms$)



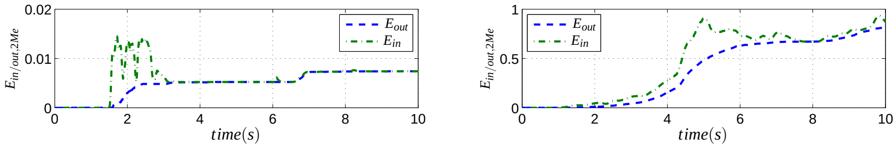
(c) Passivity Proof ($\beta_{ME} = 1$, $T_i = 50ms$) (d) Passivity Proof ($\beta_{ME} = 0.75$, $T_i = 50ms$)

Fig. 10. Performance and Passivity Proof of the track-PO/PC system, with channel delay of 50ms and varying authority allocation in a PF-architecture

In figure 11(a) a shared authority situation is displayed. The slave is now exactly positioned in the middle of the two operators. The operators' passivity controllers dissipate about the same amount of energy.



(a) Performance ($\beta_{ME} = 0.5$, $T_i = 50ms$) (b) Performance ($\beta_{ME} = 0.25$, $T_i = 200ms$)



(c) Passivity Proof ($\beta_{ME} = 0.5$, $T_i = 50ms$) (d) Passivity Proof ($\beta_{ME} = 0.25$, $T_i = 200ms$)

Fig. 11. Performance and Passivity Proof of the track-PO/PC system, with varying channel delay and authority allocation in a PF-architecture

In the last experiment the delay was chosen to 200ms per communication channel. The position following of the devices is still satisfactory (see 11(b)). E.g. from second eight to nine the operators have the same intention and thus the same position. The slave's position is delayed by approximately 0.2s as expected.Regarding the experiments conjointly (see 10(a)-11(d)) one can recognize that the amount of dissipated energy (E_{PC}) increases with the delay since the channel's activity rises. Furthermore it can be seen that the PC of the guiding operator (mentor for $\beta_{ME} > \beta_{TR}$ and vice versa) dissipates less energy than the one of the trained operator.

5 CONCLUSIONS AND FUTURE RESEARCH

The TDPA has been applied to a trilateral system in a generic way. Choosing the adequate communication channel and control unit moduls different control architectures can be implemented in the peer-to-peer system. The experiments showed good results for roundtrip delays up to 200ms. The authority allocation system has been optimized resulting in satisfying position following of the three peers. The PF and the PP control architecture (which has not been presented in this paper) are already modeled. Those control architectures concentrate on the training of trajectories. Presenting the force sensed by the slave device will in the future improve the perception of the slave's environment. Therefore another control unit and communication channel set for the 4Ch architecture will be developed. The energy behaviour of the introduced authority allocation and the PI controller was analysed and respected in the PO/PC design. The track-PO/PC controlling two tracks conjointly leads to the most robust approach compared to the straight forward appliance of the bilateral channel-PO/PC. Nevertheless the track-PO/PC conservativity depends strongly on the choice of PI-controller parameters. The applied passivity controllers with impedance causality generate high-frequent forces. For that reason a technique introducing a virtual mass spring system [8] has already been integrated. This proceeding will in future works be compared to the usage of admittance PCs [6].

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