2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Time Domain Passivity Control for Multi-Degree of Freedom Haptic Devices with Time Delay

Katharina Hertkorn, Thomas Hulin, Philipp Kremer, Carsten Preusche and Gerd Hirzinger

Abstract— **This paper generalizes the Time Domain Passivity Control concept originally introduced by J.-H. Ryu et al. (2004) in order to work for multi-degree of freedom (DoF) haptic systems with time delay. Its energy computation (named passivity observer) factors in the phase shift caused by time delay, and is improved by an energy estimation. Moreover, the variable damping of the passivity controller is generalized such that weighting by the mass matrix of the haptic device is possible. This transformation takes into account the direction-dependent inertia of multi-DoF haptic devices. Furthermore, a stability boundary for this damping is introduced for one as well as for several DoF allowing for high energy dissipation. Additionally, it is briefly shown that one single multi-DoF Cartesian passivity controller is advantageous compared to independent single-DoF passivity controllers in each joint of the haptic device. Finally, the generalized Time Domain Passivity Controller is experimentally verified using the DLR light weight robot arm as haptic device.**

I. Introduction

Virtual environments can be felt and touched by a human operator using a haptic device. To secure safe and transparent interaction, control strategies are needed that guarantee stability in any circumstance.

In a typical haptic system where digital elements (e.g. virtual environment, haptic device controller) are coupled to continuous-time parts (e.g. human operator, mechanical parts of the haptic device), effects like sampling [1], quantization [2], structural elasticity [3] or delay [4] can cause energy gain and destabilize the haptic system. A well known approach for stabilizing a haptic system is to guarantee passivity of its elements. Colgate and Schenkel [5] derived a condition for passivity of a haptic system. Yet, this condition is conservative, since it holds independently of environmental and user properties.

Hannaford and Ryu [6] introduced a less conservative control strategy also based on passivity named Time Domain Passivity Control (TDPC). Their controller adjusts a variable damping such that it dissipates exactly the amount of net energy output. Ryu et al. improved the TDPC concept e.g. by considering the phase shift due to time-discretization [7], applying it to multi-Degrees of Freedom (DoF) interaction with virtual environments [8], and avoiding its noisy behavior [9].

Due to communication time every haptic device is inherently affected by time delay. Although this time delay might be small it causes an additional error in the energy computation of the TDPC next to the errors caused by discretization and the sampling rate. Another problem applying the previous presented controller to a multi-DoF haptic system originates from a missing weighting of the variable damping depending on the inertia of the haptic device.

The authors are with the German Aerospace Center (DLR), Institute of Robotics and Mechatronics, Oberpfaffenhofen, D-82234 Wessling; email addresses have the structure {forename.surname}@dlr.de.

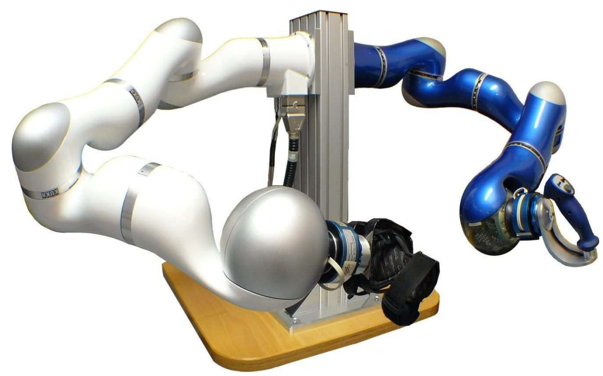


Fig. 1: DLR's Bimanual Haptic Interface

Thus, the present article generalizes the TDPC approach, such that it accounts for

- constant time delay,
- multi-DoF haptic devices,
- and direction-dependent inertia.

This generalized control strategy is evaluated with the DLR light weight robot arm as haptic device [10], see Fig. 1.

The article is structured as follows: Section II gives a brief review of Ryu's TDPC. Upon this, above mentioned extensions are elaborated in section III. In section IV two possible implementations for the multi-DoF control are presented and discussed. Section V confirms the validity of the generalized TDPC approach by experiments with the light weight robot before concluding in section VI.

II. Review of the Time Domain Passivity Controller

In this section, a short review of the TDPC presented 2004 by Ryu et. al [7] is given. To clearly differentiate between physical signals of the observed system and those based on sensor information, variables are marked with a bar if their physically existing value is addressed, e.g. $\bar{E}$ for the physical energy of a system. Furthermore, the sign convention for all forces and velocities is such that their product is positive when power enters the system port.

The basic principle of Ryu's discrete TDPC is based on the widely known definition of passivity of a time-continuous system [6]:

Definition 1: A one-port network N with initial storage energy $\bar{E}(0)$ at time $t = 0$ is *continuous-time passive* if and only if

$$\int_0^t \bar{f}(\tau)\bar{v}(\tau)d\tau + \bar{E}(0) \geq 0 \quad \forall\, t \geq 0 \tag{1}$$

for force $\bar{f} \in \mathbb{R}$ and velocity $\bar{v} \in \mathbb{R}$.

In analogy to this, Ryu et al. defined sample-time passivity as follows.

Definition 2: A network N with initial storage energy $\bar{E}_0$ at time $t_0 = 0$ and physical energy $\bar{E}_k$ is *sampled-time passive* if and only if

$$\bar{E}_k + \bar{E}_0 \geq 0 \quad \forall\, k \in \mathbb{N}, \tag{2}$$

for each point in time $t_k = k \cdot T$, where T denotes the sampling period.

If $\bar{E}_k + \bar{E}_0 < 0$ for at least one point in time t_k, the network is active. In this case the amount of energy leaving the system port is $-(\bar{E}_k + \bar{E}_0)$.

A haptic system consisting of a virtual reality (VR) simulation, a haptic device and its control operated by a human is now considered. Since a human operator interacts passively with a passive system [11], the complete haptic system is sampled-time stable, if (2) holds at each sampling step t_k. The TDPC concept guarantees passivity of a network N by dissipating generated energy with a variable damper, named passivity controller (PC). Since the exact physical energy $\bar{E}_k$ of this network is not known a priori, it has to be estimated based on sensor information of the haptic device. The calculation rule for the energy E_k is called passivity observer (PO).

Consider a discrete-time network N that takes the position $\bar{x}_k \in \mathbb{R}$ as its input, and force $\bar{f}_k \in \mathbb{R}$ as its output. Then the PO calculates the energy $E_k \in \mathbb{R}$ at each time step t_k as

$$\begin{aligned} E_k &= \overbrace{T\sum_{i=0}^{k}\Big(f_{i-1}(x_i - x_{i-1})\Big)}^{E_{\text{obs},k} \approx \bar{E}_k} + \overbrace{T f_k(x_k - x_{k-1})}^{\Delta E_{\text{est},k}} \\ &\approx \bar{E}_{k+1}, \end{aligned} \tag{3}$$

under the assumption $x_{-1} = x_0,\ f_{-1} = 0$.

The PO estimates at the current time step t_k the physical energy $\bar{E}_{k+1}$ of the system at the next time step, after the force f_k would have acted. The energy calculation (3) of the PO consists of two parts: the observed energy $E_{\text{obs},k}$ and the estimated energy $\Delta E_{\text{est},k}$. $E_{\text{obs},k}$ mirrors the physical energy $\bar{E}_k$ of the network at time step t_k. By delaying the force f by one sampling period the phase shift between f and the position x caused by sampling is taken into account assuming no further delay in the haptic system. With $\Delta E_{\text{est},k}$, the energy change between the current time step t_k and the next time step t_{k+1} is estimated assuming constant velocity.

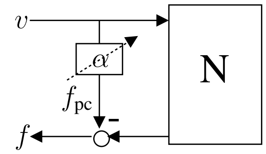


Fig. 2: One-port network with PC

If the system is active at an instance t_k the amount of energy $-E_k$ leaving the system port is dissipated by the force $f_{\text{pc},k} \in \mathbb{R}$ of the PC:

$$f_{\text{pc},k} = \begin{cases} \alpha_k v_k = \frac{-E_k}{T v_k}, & \text{for } E_k < 0 \\ 0, & \text{for } E_k \geq 0, \end{cases} \tag{4}$$

where $v_k = (x_k - x_{k-1})/T$ represents the discrete calculation of the velocity. In this one-DoF case the control parameter damping $\alpha_k \in \mathbb{R}$ is calculated as [6]:

$$\alpha_k = \begin{cases} \frac{-E_k}{T v_k^2}, & \text{for } E_k < 0 \\ 0, & \text{for } E_k \geq 0. \end{cases} \tag{5}$$

In Fig. 2 a one-port network N with the passivity control scheme is shown. The force of the passivity controller f_{pc} is directed opposite to velocity v and thus decelerates the system. The dashed arrow illustrates the variable damping α.

In the multi-DoF case with $\mathbf{f}_{\text{pc},k}, \mathbf{v}_k \in \mathbb{R}^p$, $p > 1$ damping was generalized by Preusche et al. [8]:

$$\alpha_k = \begin{cases} \frac{-E_k}{T \mathbf{v}_k^T \mathbf{v}_k}, & \text{for } E_k < 0 \\ 0, & \text{for } E_k \geq 0. \end{cases} \tag{6}$$

PO and PC calculate in analogy to the one-DoF case.

Above approach of the TDPC is limited to undelayed haptic systems and does not consider dynamics of the haptic device. In the following section an extension of this concept is presented adopting the TDPC to haptic systems where those assumptions do not hold.

III. Extension of the Time Domain Passivity Controller

In this section a generalized TDPC is presented that can be applied to multi-DoF haptic systems with time delay. Fig. 3 shows the physical setup of the considered haptic system with time delay. The extension of the TDPC is divided into three parts: Adjusting the PO, generalizing the calculation of damping in the PC, and introducing an upper limit for damping.

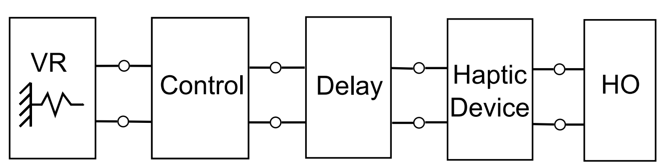


Fig. 3: Physical setup of the considered haptic system

A. The PO for Delayed Systems

The first step towards a generalized TDPC is to improve the energy observation of the system. The round trip delay T_d of the considered system is assumed to be a multiple of the sampling period T

$$T_d = d \cdot T, \quad d \in \mathbb{N}. \tag{7}$$

It is also symmetrical meaning that it takes $d/2$ sampling steps until the sensor signals are received and $d/2$ sampling steps until the commanded force applies.

In the following the multi-DoF notation of the TDPC is used with $\mathbf{f}_k, \mathbf{x}_k \in \mathbb{R}^p$, $p > 1$.

The generalized PO consists of two parts following (3): First, the observed energy $E_{\text{obs},k}$ is adapted by delaying the force by $d+1$ sampling steps. Thus, the phase shift caused by both time discretization and round trip delay are considered:

$$E_{\text{obs},k} = \sum_{i=0}^{k} \mathbf{f}_{i-d-1}^T (\mathbf{x}_i - \mathbf{x}_{i-1}) \approx \bar{E}_{k-d/2} \tag{8}$$

with

$$\mathbf{x}_{-1} = \mathbf{x}_0, \mathbf{f}_{-\varsigma} = \mathbf{0}, \quad \varsigma \in \mathbb{N}. \tag{9}$$

In contrast to the first summand of (3) this energy observation does not mirror the physical energy at the current time step t_k but it matches with the physical energy $d/2$ sampling steps before the current time step, which is the time delay until the measured sensor signals of the haptic device are received.

Second, $\Delta E_{\text{est},k}$ needs to estimate the physical energy change from time step $t_{k-d/2}$ to $t_{k+d/2+1}$. This is exactly the time period until and while the commanded force of the PC is executed but its effects are unknown to the PO. This estimation can be achieved using estimated velocities of the haptic device $\widetilde{\mathbf{v}}_k$:

$$\Delta E_{\text{est},k} = \sum_{j=k+1}^{k+d+1} T \mathbf{f}_{j-d-1}^T \widetilde{\mathbf{v}}_j \approx \bar{E}_{k+d/2+1} - \bar{E}_{k-d/2}. \tag{10}$$

An accurate velocity estimation is a key point in (10). Naturally, there are many types of estimation methods possible, e.g. keeping the velocity constant during the delay as Ryu presented, calculating the velocity based on extrapolation or considering the model of the haptic device. Estimation methods are evaluated in section V-A.

Altogether, the PO estimates the physical energy $\bar{E}_{k+d/2+1}$ at each time step t_k, limited by the accuracy of measurement and the velocity estimation, as

$$E_k = E_{\text{obs},k} + \Delta E_{\text{est},k} \approx \bar{E}_{k+d/2+1}. \tag{11}$$

B. Generalized Calculation of Damping

The second step is generalizing the damping of the PC for the multi-DoF case where $\mathbf{f}_{\text{pc},k}, \mathbf{v}_k \in \mathbb{R}^p$ with $p \in$ {Cartesian degrees of freedom, number of joints}: If the system is active at a time step t_k, the amount of generated energy $-E_k$ has to be dissipated such that the system is passive and the sum of generated and dissipated energy is zero:

$$E_k + E_{\text{damp},k} = 0 \ \{\forall\, k | E_k < 0\}. \tag{12}$$

The amount of dissipated energy is calculated in analogy to the system's energy considering the phase shift between force and velocity as the force of the PC applies delayed to the haptic system:

$$E_{\text{damp},k} = T \mathbf{f}_{\text{pc},k}^T \widetilde{\mathbf{v}}_{k+d+1}. \tag{13}$$

This underlines the importance of a correct velocity estimation.

Holding for the one-DoF case $f_k, v_k \in \mathbb{R}$ and $d = 0$, the damping parameter α_k in (5) can be easily derived by solving (12) and substituting $f_{\text{pc},k} = \alpha_k v_k$ in (13). Thereby constant velocity between the time steps t_k and t_{k+1} is assumed.

Generalizing α_k for the multi-DoF case to a $p \times p$ damping matrix $\mathbf{A}_k$, (12) changes to

$$\widetilde{\mathbf{v}}_{k+d+1}^T \mathbf{A}_k^T \widetilde{\mathbf{v}}_{k+d+1} = \frac{-E_k}{T}, \tag{14}$$

which has no unique solution for the p^2 unknowns in $\mathbf{A}_k$. Assumptions about $\mathbf{A}_k$ have to be made to uniquely solve the equation. The trivial solution $\mathbf{A}_k = a_k \mathbf{I}$ is equivalent to above statement (6) using a multiple of the identity matrix. Aiming to obtain the same deceleration in each DoF, damping must be weighted by inertia, and therefore yields

$$\mathbf{A}_k = a_k \widetilde{\mathbf{M}}_{k+d+1}, \tag{15}$$

where $\widetilde{\mathbf{M}}_{k+d+1}$ is the mass matrix representing the inertia of the haptic device in each Cartesian direction at time t_{k+d+1}. Once more the time delay needs to be considered and thus, the mass matrix must be estimated similar to the velocity estimation.

The number of unknowns in (14) reduces to one, and a unique solution for the damping results as

$$a_k = \frac{-E_k}{T \widetilde{\mathbf{v}}_{k+d+1}^T \widetilde{\mathbf{M}}_{k+d+1}^T \widetilde{\mathbf{v}}_{k+d+1}}. \tag{16}$$

C. A Limit for Damping

As virtual damping is limited in time-delayed, stable systems [12], the third step of generalizing the TDPC is bounding the damping parameter of the PC. In [12] stability regions for haptic rendering are introduced for a single DoF haptic system. In order to stay inside these stable regions and to enable high dissipation, the damping factor of the PC is limited by

$$\alpha_{\text{max}} = \frac{m}{(1+d)T}, \tag{17}$$

under the assumption $\widetilde{\mathbf{v}}_{k+d+1} = \mathbf{v}_k$.

This boundary is constant over time, and only depends on the delay d, the mass of the haptic device m and the sampling period T. This limit also counteracts the noisy behavior of the original TDPC reported in [9], which originates from high damping factors at low velocities.

In the multi-DoF case the single mass m changes to the mass matrix $\mathbf{M}$: If the haptic device moves in a direction with high inertia, the damping of the control force can be higher without leaving the stable region, see [12] for details. In this case the boundary is a $p \times p$ matrix with $p \in \{$Cartesian degrees of freedom, number of joints$\}$:

$$\mathbf{A}_{\max,k} = \frac{\mathbf{M}_k}{(1+d)T}. \tag{18}$$

under the additional assumption $\widetilde{\mathbf{M}}_{k+d+1} = \mathbf{M}_k$.

This boundary is proportional to the mass matrix $\mathbf{M}_k$, which depends on the configuration of the haptic device and therefore changes over time. To assure stability following equation must hold:

$$\mathbf{v}_k^T \mathbf{A}_k^T \mathbf{v}_k \leq \mathbf{v}_k^T \mathbf{A}_{\max,k}^T \mathbf{v}_k \tag{19}$$

Substituting (15) and (18) into (19) a time independent boundary for the damping factor can be derived:

$$a_k \leq \frac{1}{(1+d)T} = a_{\max}. \tag{20}$$

D. The Generalized TDPC

Summing up, the generalized TDPC can be applied to a haptic system with time delay and a multi-DoF haptic device while considering direction-dependent inertia. Using above improvements it is calculated as follows:

The PO estimates the physical energy $\bar{E}_{k+d/2+1}$:

$$E_k = \sum_{i=0}^{k} \mathbf{f}_{i-d-1}^T (\mathbf{x}_i - \mathbf{x}_{i-1}) + \sum_{j=k+1}^{k+d+1} T \mathbf{f}_{j-d-1}^T \widetilde{\mathbf{v}}_j \tag{21}$$

with

$$\mathbf{x}_{-1} = \mathbf{x}_0, \mathbf{f}_{-\varsigma} = \mathbf{0}, \quad \varsigma \in \mathbb{N}. \tag{22}$$

The variable damping of the PC dissipates energy such that the haptic system is passive. Thereby $\widetilde{\mathbf{M}}_{k+d+1} = \mathbf{M}_k$ is assumed, i.e. the mass matrix is constant during the delay:

$$\mathbf{f}_{\mathrm{pc},k} = \begin{cases} \mathbf{A}_k \widetilde{\mathbf{v}}_{k+d+1}, & \text{for } E_k < 0 \\ 0, & \text{for } E_k \geq 0 \end{cases} \tag{23}$$

with $\mathbf{A}_k = a_k \mathbf{M}_k$ and

$$a_k = \min\left(\frac{-E_k}{T \widetilde{\mathbf{v}}_{k+d+1}^T \mathbf{M}_k^T \widetilde{\mathbf{v}}_{k+d+1}}, a_{\max}\right). \tag{24}$$

IV. Implementation of the Generalized Multi-DoF Time Domain Passivity Controller

To make the step from a one-DoF haptic system to a multi-DoF system, one has to adapt the controller design. Most haptic system controllers are either joint-space or Cartesian-space based. Accordingly, the multi-DoF TDPC can be implemented in either ways. This section compares the two following possibilities for multi-DoF haptic devices:

- A straightforward implementation of the joint-space based TDPC with a decentralized structure, i.e. one independent controller per joint.
- One multi-DoF Cartesian-space based TDPC with a centralized control structure.

An ideal haptic system is perfectly transparent, i.e. a system where a human operator cannot distinguish between a real operation and a simulated one. Two independent criteria are employed to evaluate the performance of the two control structures with regard to transparency: the amount of dissipated energy [13] and the disturbance of the direction of the VR force [8].

The idea behind the first criterion is keeping most information which can be displayed to the user. Dissipating energy is equal to discard information. Therefore, the less energy loss the better. The second criterion results from physics. Basically the force directions calculated in the VR are physically correct, as close as the simulation can get, so it should be matched by the haptic device and should not be disturbed by the controller.

In both criteria the Cartesian-space based controller seems to be favorable and is chosen for the multi-DoF system in the remainder of this work.

The decentralized structure of the joint-based controller requires every joint to be passive, whereas the centralized structure only has one energy balance and is therefore less conservative.

As the damping of each joint occurs independent of every other joint in the decentralized structure, the direction of the resulting force is changed according to the damping required by each joint. In contrast the Cartesian-space based approach allows for controlling the direction of the resulting force.

V. Experimental Results

The presented approach was implemented and tested on a haptic system configured according to Fig. 3. DLR's Bimanual Haptic Interface [10] is used as haptic device, which consists of two Light Weight Robot arms (LWR) running at a sampling rate of $T = 1\,\mathrm{kHz}$, see Fig. 1.

The robot arms are equipped with internal electronics, including torque sensors. They enable backdriveable behavior and operating the robot impedance controlled. In this system the round trip delay T_d between the robots and the real time computer, where the control and the calculations for the virtual reality are performed, accounts for $T_d = 4\,\mathrm{ms}$, thus $d = 4$.

In this section three experiments are presented: One to evaluate the accuracy of different velocity estimation methods, a second to verify the adjustment of the PO, and a last to show the effect of the generalized PC. In all experimental setups the virtual reality is simplified as a virtual wall represented by a stiff spring.

A. Evaluation of Different Velocity Estimation Methods

As mentioned in section III-A velocity estimation is a key point in accurately calculating the physical energy $\bar{E}_{k+d/2+1}$ of the haptic system (21). Three estimation methods are evaluated: assumption of constant velocity during the delay, first and second order extrapolation of previous velocity data. The time window on which the extrapolations are based is experimentally chosen to be ten sampling steps as it produced the most accurate results.

The estimation methods are evaluated by comparing them to a best estimation curve E_b that is calculated offline using

TABLE I: Evaluation of the velocity estimation methods

Estimation method	ΔE (Nm)
Constant velocity E_c	0.89
Linear velocity estimation E_l	0.56
Polynomial velocity estimation E_p	0.47
No estimation E_n	3.5

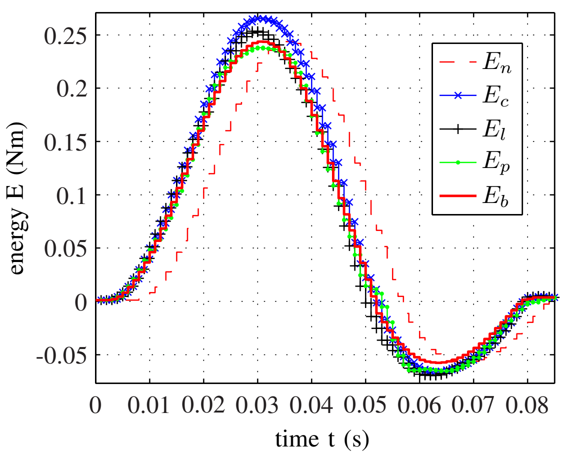
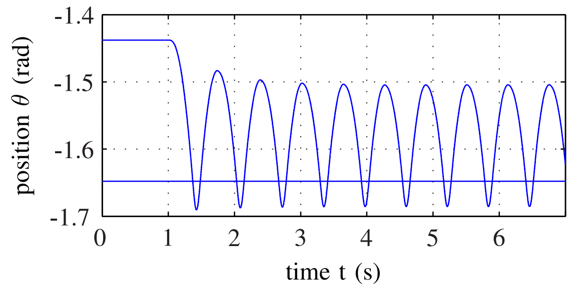


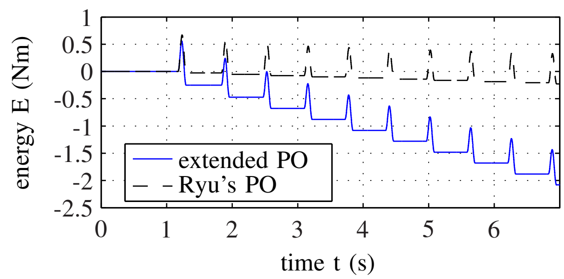
Fig. 4: Performance of the energy estimation methods

TABLE II: Parameters of the one-DoF experiments

Stiffness of the virtual wall K	15000 Nm/rad
External force τ_{ext}	3 Nm
Position of the virtual wall q_w	-1.65 rad
Starting position of the joint q_s	-1.44 rad



(a) Position



(b) Energy

Fig. 5: Contact without Time Domain Passivity Control

the measured velocities instead of the estimated ones. The root mean square error ΔE includes only λ time steps where velocity is being estimated:

$$\Delta E = \sqrt{\frac{\sum_{i=0}^{\lambda}(E_{b,i} - E_i)^2}{\lambda}}. \tag{25}$$

During the conducted experiment a human operator moves one LWR and pushes it against the virtual wall several times with different velocities and forces. This ensures a general evaluation of the estimation methods. Table I shows the result of the experiment, Fig. 4 visualizes it exemplary.

The main difference between the three approaches is their behavior during fast velocity changes. Accordingly, the energy calculated with the polynomial velocity estimation E_p (marked with dots) stays closest to the best estimation curve E_b (solid line), followed by the linear extrapolation approach E_l (marked with vertical lines). Constant velocity E_c (marked with crosses) results in a considerable overshoot. The energy without velocity estimation (E_n, dashed line) is displayed to outline the importance of energy estimation.

B. Verification of the adjusted PO

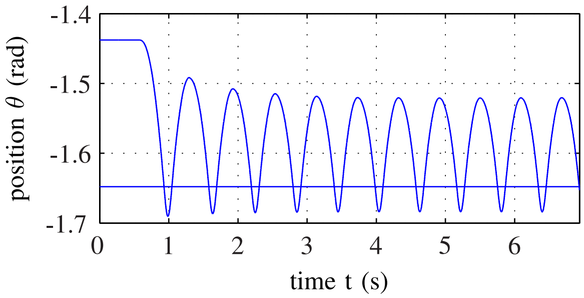
The set of experiments verifying the adjustment of the PO is presented for the one-DoF case. Multi-DoF experiments gave equivalent results but are not shown here for the sake of clarity. One joint of one LWR is pushed into a virtual wall by a constant external force τ_{ext}. The stiffness $K = 15000\,\frac{\text{Nm}}{\text{rad}}$ of the implemented virtual wall is chosen to be significant above the stability limit for the used haptic system, which results in $K = 5330\,\frac{\text{Nm}}{\text{rad}}$ following the stability condition in [14]. The parameters for the experiments are summarized in table II.

In a first trial, the contact is established without TDPC, in a second one the TDPC proposed by Ryu in [7] and in a last trial the new control approach is evaluated.

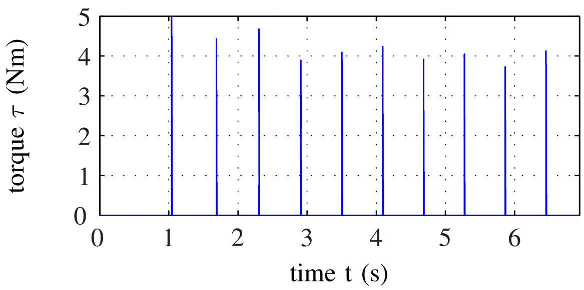
Fig. 5a mirrors the unstable behavior of the haptic system without TDPC. On account of the friction of the haptic device the unstable behavior results in an oscillation where friction and active behavior find an equilibrium point. A haptic device without friction would show destructive resonance. The effect of different energy calculations E_k is shown in Fig. 5b: The energy of the extended PO (solid curve) falls well below zero and reflects the active behavior of the haptic device. By contrast, the observation without considering time delay (dashed curve) stays close to zero.

Using Ryu's approach the contact with the virtual wall shows still unstable behavior, as can be seen in Fig. 6a. This is contrary to the behavior of the energy observation which implies stable behavior, see Fig. 6b. Therefore, the energy observation does not reflect the existing energy at the haptic device since it does not consider time delay. The small amount of dissipated energy, see Fig. 6c, reduces the amplitude and the frequency of the oscillation but does not lead to stability.

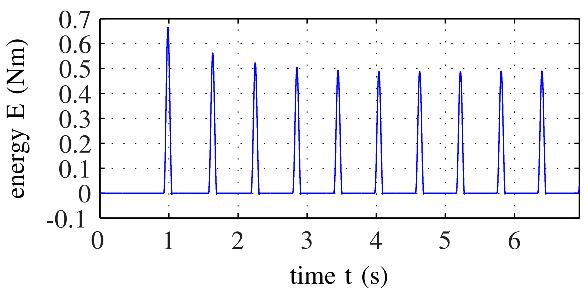
A stable behavior is finally achieved by using the generalized TDPC, see Fig. 7a. The PO recognizes the active behavior of the haptic device by accurately estimating the energy. Therefore, the right amount of energy can be dissi-



(a) Position

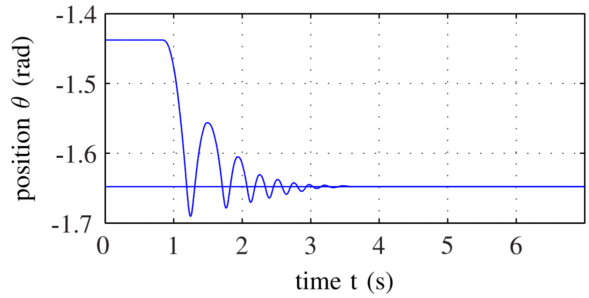


(b) Passivity control torque

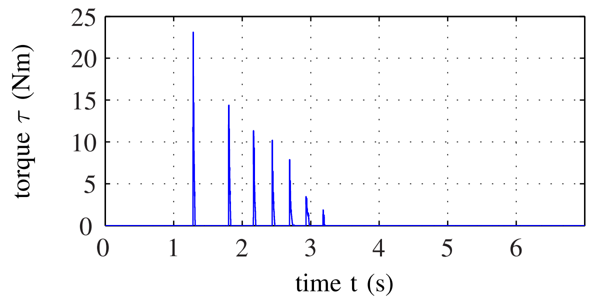


(c) Energy

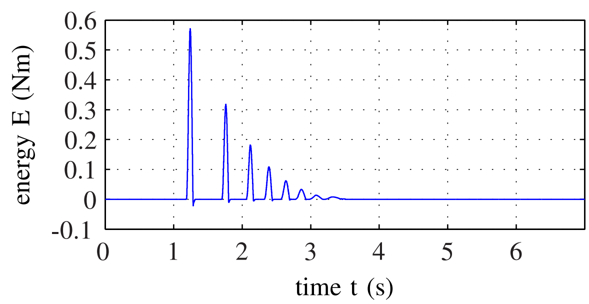
Fig. 6: Contact with Time Domain Passivity Control (Ryu)



(a) Position



(b) Passivity control torque



(c) Energy

Fig. 7: Contact with generalized Time Domain Passivity Control

TABLE III: Parameters of the multi-DoF experiments

External Torque $\boldsymbol{\tau}_{\text{ext}}$	$[0, 15, 0, -6, 0, 0, 0]$Nm
Duration of the Acceleration	$0.2\,\text{s}$
External Energy E_{ext}	$-2\,\text{Nm}$

pated and the haptic device is stabilized, see Fig. 7b and 7c. The friction of the system dissipates additional energy and that is why the haptic device settles on the wall.

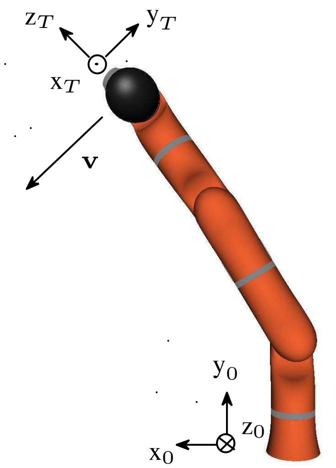
C. Verification of the generalized PC

To show the importance of weighting the variable damping of the PC with the mass matrix of the haptic device a third experiment is conducted using the generalized multi-DoF TDPC approach: the LWR is accelerated from $t = 0\,\text{s}$ to $t = 0.2\,\text{s}$ by an external torque τ_{ext}, see table III. While the LWR is moving undisturbed in a free workspace, the energy of the PO is artifially set to $E_k = -2\,\text{Nm}$ at $t = 0.3\,\text{s}$ and the PC starts to dissipate this simulated energy. By doing so, the stable movement of the haptic device is influenced by the damping force of the passivity controller.

Fig. 8a shows the configuration of the haptic device at the beginning of the experiment including the world coordinate system (x_0, y_0, z_0) and the tool coordinate system (x_T, y_T, z_T). The LWR is close to a singularity, which leads to a bad conditioned mass matrix $\mathbf{M}_k$ (given in tool coordinates), see Fig. 8b. Especially in those configurations close to singularities it is important that the force of the PC takes the mass matrix into account as can be seen in the following.

Three trials of the experiment are conducted and shown in Fig. 9. One without artificial energy reset (line marked with dots), a second where the PC does not consider the inertia of the haptic device (blue solid line) and a last where the mass matrix is considered in the damping force of the PC (red dashed line). The circle marks the artificial reset of the PO to $-2\,\text{Nm}$ at $t = 0.3\,\text{s}$ in the last two trials.

It can be seen that the movement of the haptic device drifts considerably neglecting the mass matrix due to applying the same damping parameter to all directions of motion. Thus,



(a) Configuration of the LWR

5	0.3	2.8	−0.003	−0.08	0.0002
0.3	37	129	−0.06	0.22	0.05
2.8	129	494	0.01	0.5	0.005
−0.003	−0.06	0.01	0.009	0.002	−0.004
−0.08	0.22	0.5	0.002	0.16	0.002
0.0002	0.05	0.005	−0.004	0.002	0.004

(b) Mass matrix $\mathbf{M}_k$ (kg)

Fig. 8: Experimental setup for section V-C

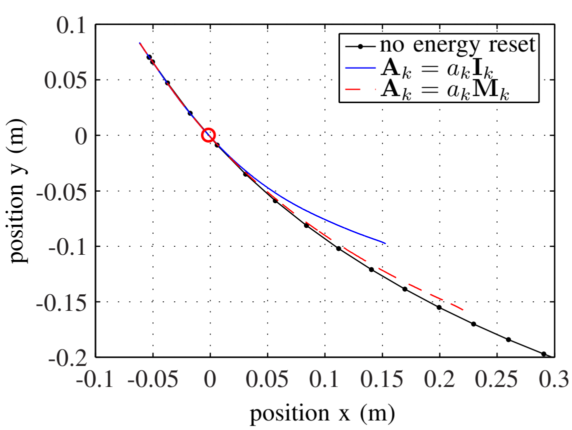


Fig. 9: Movement of the end effector of the haptic device

directions with low inertia experience higher deceleration then those with large values in the mass matrix. By contrast, considering the direction-dependend inertia in the damping force results in a trajectory close to the one in free movement.

VI. Conclusion and Future Works

This paper introduced a generalized TDPC concept that can be applied to multi-DoF haptic systems with time delay. By adjusting the calculation rule of the PO the physical energy of the haptic system is estimated accurately, such that the PC can stabilize the system. By generalizing the calculation of the damping in the multi-DoF control direction-dependent inertia of the haptic device is considered. Additionally, a limit for damping was introduced to maintain stability for delayed systems. Experiments validated the generalized approach.

Future works contain deriving a less conservative stability boundary without assuming constant velocity and mass matrix. Additionally, it seems promising to utilize more accurate velocity estimation methods that make use of a haptic device model.

References

[1] C. Basdogan and M. Srinivasan, *Handbook of Virtual Environments*. Lawrence Erlbaum Associates, Inc., 2001, ch. Haptic rendering in virtual environments, pp. 117–134.

[2] J. Abbott and A. Okamura, "Effects of position quantization and sampling rate on virtual-wall passivity," *IEEE Transactions on Robotics*, vol. 21, no. 5, 2005.

[3] I. Diaz and J. Gil, "Influence of internal vibration modes on the stability of haptic rendering," in *Proc. of the IEEE Int. Conf. on Robotics and Automation (ICRA)*, Pasadena, CA, May 2008, pp. 2884–2889.

[4] C. Secchi, S. Stramigioli, and C. Fantuzzi, "Delayed virtual environments: a port-hamiltonian approach," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, Oct. 2003, pp. 2956–2961.

[5] J. Colgate and G. Schenkel, "Passivity of a class of sampled-data systems: Application to haptic interfaces," *Journal of Robotic Systems*, vol. 14, 1997.

[6] B. Hannaford and J.-H. Ryu, "Time domain passivity control of haptic interfaces," *IEEE Transactions on Robotics and Automation*, vol. 18, no. 1, pp. 1–10, 2002.

[7] J.-H. Ryu, Y. Kim, and B. Hannaford, "Sampled and continuous time passivity and stability of virtual environments," *IEEE Transactions on Robotics (The successor of IEEE Trans. on Robotics and Automation)*, vol. 20, no. 4, pp. 772–776, 2004.

[8] C. Preusche, G. Hirzinger, J.-H. Ryu, and B. Hannaford, "Time domain passivity control for six degrees of freedom haptic displays," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, Oct. 2003, pp. 2944–2949.

[9] J.-H. Ryu, B. Hannaford, D.-S. Kwon, and J.-H. Kim, "A simulation/experimental study of the noisy behavior of the time-domain passivity controller," *IEEE Transactions on Robotics*, vol. 21, no. 4, 2005.

[10] T. Hulin, M. Sagardia, J. Artigas, S. Schätzle, P. Kremer, and C. Preusche, "Human-scale bimanual haptic interface," in *Proc. of the 5th International Conference on Enactive Interface*, no. 5, Pisa, Italy, Nov. 2008.

[11] N. Hogan, "Controlling impedance at the man/machine interface," in *Proc. of the IEEE Int. Conf. on Robotics and Automation (ICRA)*, vol. 3, May 1989, pp. 1626–1631.

[12] T. Hulin, C. Preusche, and G. Hirzinger, "Stability boundary and design criteria for haptic rendering of virtual walls," in *Proc. of the 8th International IFAC Symposium on Robot Control*, Bologna, Italy, Sept. 2006.

[13] Y. Kim and B. Hannaford, "Some practical issues in time domain passivity control of haptic interfaces," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, vol. 3, Maui, Hawaii, Oct. 2001, pp. 1744–1750.

[14] J. Gil, E. Sánchez, T. Hulin, C. Preusche, and G. Hirzinger, "Stability boundary for haptic rendering: Influence of damping and delay," *Journal of Computing and Information Science in Engineering*, vol. 8, no. 3, Sep. 2009.