Actuator Capabilities Aware Limitation for TDPA Passivity Controller Action

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***Abstract*— Haptic interaction often requires stabilizing controllers for safety. The Time-Domain Passivity Approach guarantees passivity (then stability) by observing and dissipating energy generated from active elements in a network. The dissipating action is performed by a *Passivity Controller*, whose action is commanded to the physically limited robot actuators. Thus, the controller stabilizing action should be in turn limited in order to command displayable references to the actuators. This problem is rarely taken into account in the literature and when it is, the limitation is neither directly related to the actuator power limits, nor to the robot's current configuration. The limits of the currently adopted strategies leave room for improvement. In this paper, a new strategy to limit the Passivity Controller action is proposed taking into account both the physical limits of the actuators and the robot configuration. This new strategy is experimentally tested against the classical one based on the sampling time. In the experiment, a human interacts with a virtual wall in a Virtual Environment through a haptic interface. The wall induces an unstable behavior passivated with the two limitation strategies. The results clearly state the benefits introduced by the proposed strategy in two relevant cases.**

I. INTRODUCTION

Haptic interfaces for interactions in virtual environments and teleoperation architectures for bilateral force reflection share the necessity for stability control. In fact, it is well known that in both these fields phenomena like quantization, sampling and time delay constitute sources of instability for the devices [1], [2]. Passivity is a sufficient condition for stability and is much simpler to be monitored with regard to stability. Thus, many passivity-based approaches have been developed to guarantee the stability of haptic interfaces and teleoperation architectures [3], [4], [5], [6]. One of the most successful approaches is the *Time Domain Passivity Approach (TDPA)* [7], [8], [9]. This was originally developed for *1-Degree-of-Freedom (1-DoF)* and successively extended for *n-Degrees-of-Freedom (n-DoFs)* [10], [11], represents the architecture as a block network. In such a network, the energy at the port of each block that may exhibit active behavior is observed by a *Passivity Observer (PO)* and dissipated (if energy is generated) by a *Passivity Controller (PC)*.

In this context, the *PC* is a virtual damper that modifies the control reference signal (usually force for impedance-based devices and velocity for admittance-based devices) in order to dissipate the observed energy with a stabilizing action. The aim of a *PC* is to dissipate the overall observed energy in one sample. However, this clashes with the physical possibilities of real robots. In particular, robots have power-limited actuators and it is very common that the stabilizing action required from the *PC* exceeds the torque or speed limits that can be performed by the actuators. Moreover, the effectiveness of the *PC* (that is the energy dissipated by the controller itself) is computed on the basis of the requested stabilizing action, not considering if this action is really performed by the actuators. When the stabilizing action exceeds the actuator capabilities, this action may be insufficient to stabilize a robot even if the *PC* seems to work correctly.

It is then clear that limiting the *PC* stabilizing action on the base of the physical limits of the device is fundamental to guarantee correct passivation. The problem of limiting the *PC* action is known at the *state-of-the-art* for years. However, few solutions were proposed and most of these are neither directly related to the configuration nor to the power limits of the devices. In fact, most of the works proposed in the *TDPA* literature focus on reducing or cleaning the stabilizing action of the *PC* to ensure a good degree of transparency [12], [13]. Thus, limiting the *PC* action is still an open problem.

In the *state-of-the-art*, typically *PC* damping elements are limited on the basis of the delay [11], which requires an *a priori* knowledge of the communication channel (with big difficulties, in particular in presence of variable time delay), or on the base of the sampling time [14]. However, both of these limitations do not take into account the robot configuration and the power limitation of the actuators. A possible reason is that the *PC* is typically formulated in the task space while the limits of the actuators are expressed in the joint space. However, time-based *PC* limits may easily fall into stability problems: in fact, a system with high power limits actuators and low sampling time will dissipate less than what is possible, while a system with low power limits actuators and high sampling time will try to dissipate more than physically realizable.

To the best knowledge of the authors, the only proposed approach that considers power-limited actuators is proposed in [14], in which both joint and task space formulations are presented. Even if the paper focuses on the subspace-oriented dissipation, the inclusion of actuator limits is imposed as an inequality constraint that requires the on-line solution of a quadratic programming (QP) problem. The resulting computing burden makes online, real-time stand-alone applications

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(such as teleoperation) challenging or even unfeasible on wearable applications. Moreover, the approach has only been tested in simulation.

In their previous work [15], the authors considered the problem of linking the dissipating capabilities of the *PC* to the power limits of the actuators and to the configuration of the robot. The study proposed an interesting joint space *PC* limitations that considers both configuration and power-limited actuators and that only applies to redundant robots. However, the proposed solution doesn't fit the wider class of task space-controlled robots and lacks real hardware tests. Moreover, the solution proposed in [15] doesn't consider the amount of actuators' power that is already spent to track a certain reference.

In this paper, a new approach to limit the damping action of the *PC* is presented both in the case of impedance-based or admittance-based robots controlled in the task space. The proposed closed-form solution is based on the actuators' power limits and takes into account the robot's current configuration. This leads to consequent advantages with regard to the aforementioned methods. Moreover, the presented solution considers the power already exerted by the actuators to realize the reference and, differently from other methods, has been tested beyond simulation on a real haptic interface during the interaction with a virtual wall. It should be noticed that no modifications are required to the *PO* nor to the *PC* and the method is applicable in any situation in which a *PC* is required (teleoperation or virtual environment interaction).

The paper is organized as follows. Section II briefly recalls the *TDPA* methods among the accepted and proposed *PC* limitations. Section III describes the experiments performed to validate our proposed limitation with respect to currently used limitations. Then, section IV shows the achieved results. Finally, in Section V we discuss the results and conclude the paper.

II. MATERIAL AND METHODS

In this section, the *Time-Domain Passivity Approach* is briefly recalled. In the following, *state-of-the-art PC* limitation methods are reported along with the proposed limitation.

A. Time-Domain Passivity Approach

The *TDPA* aims to passivate the elements of the architecture which exhibit an active behavior guaranteeing stability. The overall architecture is represented as 2-port network blocks interconnected, making it possible to monitor the energy flowing through the blocks using *Passivity Observers (PO)* and dissipating it using *Passivity Controllers (PC)*.

Referring to figure 1, we define $\mathbf{v}$ as the haptic interface velocity vector and $\hat{\mathbf{f}}_d = \mathbf{f}_w$ as the desired force vector produced by the virtual environment. The correlated force-velocity variables are defined in order to obtain positive power entering blocks. The *PO* is formulated as follows:

$$E_{obs}(k) = \Delta T \sum_{i=0}^{k} w(i) + E_{PC}(k) = \Delta T \sum_{i=0}^{k} \mathbf{v}^T(i)\hat{\mathbf{f}}_d(i) + E_{PC}(k) \quad (1)$$

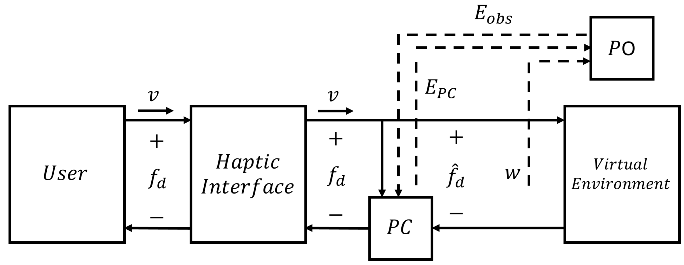

Fig. 1: Network block representation of an impedance-based haptic interface interacting with a virtual environment. The *PO* and the *PC* are placed at the port of the block that may exhibit an active behavior. It should be noticed that the user is supposed to be passive.

where $E_{PC}(k)$ is the energy dissipated by the *PC* (defined in the following) and ΔT is the sample time. Stability is guaranteed if $E_{obs}(k) \geq 0 \ \forall \ k \geq 0$, thus, if $E_{obs}(k) < 0$ the *PC* is triggered to dissipate exactly the amount of negative energy observed. The *PC* formulation depends on the causality of the device, thus for impedance-based devices the controller takes velocity inputs and produces force outputs:

$$\begin{aligned} \mathbf{f}_d(k) &= \hat{\mathbf{f}}_d(k) + \mathbf{d}(k) = \hat{\mathbf{f}}_d(k) + \alpha(k)W(k)\mathbf{v}(k) \\ \text{with } \alpha(k) &= \begin{cases} \dfrac{-E_{obs}(k)}{\Delta T \mathbf{v}^T(k)W^T(k)W(k)\mathbf{v}(k)} & \text{if } E_{obs}(k) < 0 \\ 0 & \text{if } E_{obs}(k) \geq 0 \end{cases} \\ E_{PC}(k) &= \sum_{i=0}^{k-1} \alpha(i)\mathbf{v}^T(i)W^T(i)W(i)\mathbf{v}(i) \end{aligned} \quad (2)$$

where $\mathbf{f}_d$ is final force reference modified by the *PC* and α is the virtual damping scalar. The weight matrix W allows the implementation of *n-DoFs* dissipating strategies. Currently, there is no uniquely identified best strategy and there are many possible implementations [10], [11], [16], [17]. However, it should be noticed that in many papers the suggested weight is given by the inertia matrix. In this way, the dissipating action is distributed according to the robot's mass. For the sake of readability, time dependence will be omitted from now on.

It should be noticed that, for admittance-based devices, the formulation is totally symmetrical simply exchanging forces with velocities and *vice versa*.

B. State-of-the-art time-based PC limitations

The *PC* formulation points clearly out that the algorithm aims for dissipating the overall observed energy in a single time step unless it is limited. Depending on the observed energy, it often occurs that the stabilizing action requires more power than the displayable by the actuators. It is evident the need for limiting the *PC* damping element α. In [11] it was proposed to limit the damping assuming the delay T_d of a teleoperation communication channel to be a multiple d of the sampling time:

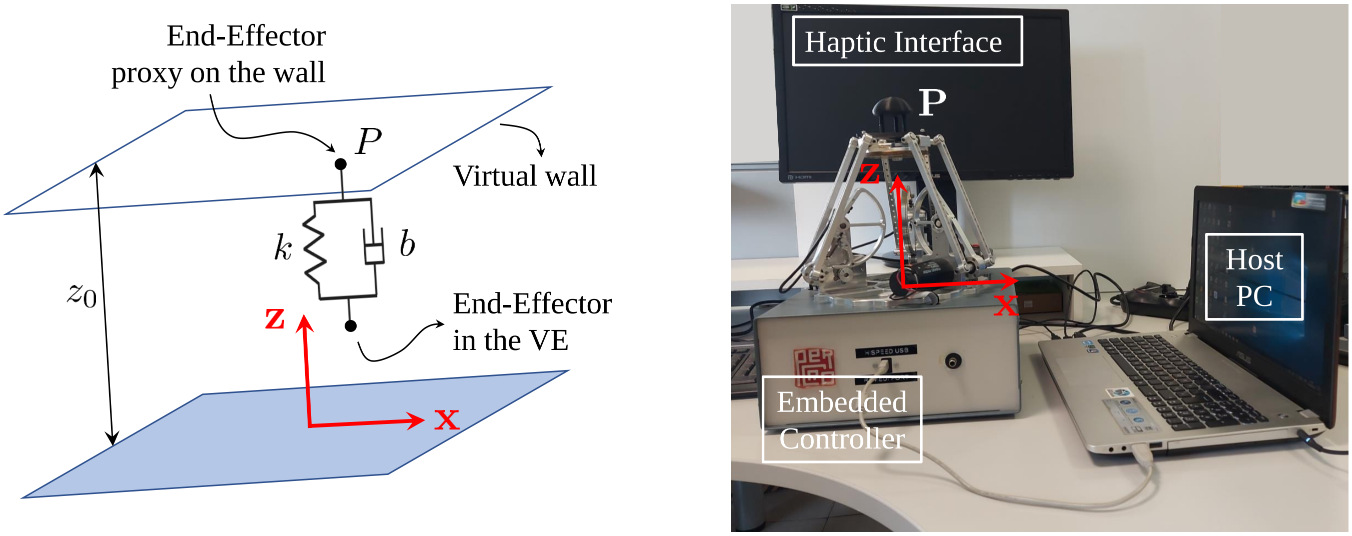

Fig. 2: Experimental setup. On the right is the haptic interface along with the embedded controller and the host PC. On the left the Virtual Environment along with the virtual wall. The reference frame is represented to co-locate the real and the Virtual Environments and introduce the notation.

$$\alpha_{MAX} = \frac{m}{T_d + \Delta T} = \frac{m}{(1+d)\Delta T} \text{ with } d \in \mathbb{N} \tag{3}$$

where m is the mass of the haptic interface. This limitation is constant, applicable in presence of time delay (teleoperation) and the time delay itself should be an integer multiple of the sample time with consequent limitations in the panorama of *TDPA*. Subsequently, in [14] it was proposed to limit the damping element on the basis of the sampling time and according to the robot kinetic energy:

$$\alpha_{MAX} = \frac{1}{2\Delta T} \tag{4}$$

Again this limitation is constant and doesn't take into account the power limits of the actuators. In particular, the limitations of this method are evident in two important cases: in the first one, a robot with high power limits and low sampling control time could possibly dissipate more energy than allowed by this limitation, while in the second one, a robot with low power limits and high sampling time is asked to produce stabilizing actions much higher than physically allowed by the actuators.

In [14], it was proposed an extended *PC* formulation that takes into account the power limit of the actuators However, it requires solving an online recursive *QP* problem. Even if this approach guarantees to respect the actuator limits, it requires a bulky calculation to be performed online for real-time (usually stand-alone) applications, such as teleoperation, and requires setting empirical parameters. Moreover, this approach does not take into account, like the previous two, the fact that actuators are also charged by the rendering torques.

C. New power-limits-based PC limitations

From what was discussed before, a suitable *PC* damping limitation should take into account actuators' limits among with the robot's actual configuration, it should be preferably formulated in a closed-form expression and it should also take into account that rendering torques decrease the maximum *PC* displayable torque. To match these needs and considering the study proposed in [15], we propose a new power-limit-based limitation for the damping element of the *PC*.

Assuming an impedance-based square robot, it is possible to uniquely define the maximum displayable force vector in the task space on the base of the maximum torque vector $\boldsymbol{\tau}_{MAX}$ displayable in the joint space:

$$\mathbf{f}_{MAX}(q) = J^{-T}(q)\boldsymbol{\tau}_{MAX} \tag{5}$$

where $J(q)$ is the robot Jacobian matrix and q is the vector of the actual joint configuration (omitted in the following for the sake of readability). It is straightforward that the stabilizing action of the PC should not exceed this $\mathbf{f}_{MAX}$, since otherwise a reference would be produced which the actuators would not be able to follow. However, it should be considered that a haptic interface aims to render a specific reference ($\hat{\mathbf{f}}_d$), therefore the power that the actuators are able to deliver must, at least in part, be spent to produce this reference. With a view to favoring the rendering of the reference, it is possible to define the residual displayable force as $\mathbf{f}_{res} = \mathbf{f}_{MAX} - \hat{\mathbf{f}}_d$, it is evident that the stabilizing action of the *PC* could not exceed the residual displayable force. Then referring to equation 2 and minding the above consideration, a suitable condition to limit the damping element is the following:

$$||\alpha W \mathbf{v}|| \leq ||\mathbf{f}_{res}|| \Rightarrow \ \alpha_{MAX} = \sqrt{\frac{(\mathbf{f}_{MAX} - \hat{\mathbf{f}}_d)^T(\mathbf{f}_{MAX} - \hat{\mathbf{f}}_d)}{\mathbf{v}^T W^T W \mathbf{v}}} \tag{6}$$

It should be noticed that the proposed α_{MAX} depends on both time and configuration and also on the power limits of the actuators. The proposed limit simply states the maximum amount of energy that the robot can dissipate in a given time step based on its configuration and the capabilities of its actuators. It is evident that no modifications are required to the structure of neither *PO* nor to the *PC*. In fact, if the overall observed energy is not completely dissipated, the remaining is simply stored for the next sample according to the *PC* algorithm. The dissipation strategy adopted among the different possibilities available in the *state-of-the-art* is taken into account through the matrix W, as defined in equation 2. It should be noticed that our residual force proposal privileges transparency, but it limits the effectiveness of the *PC*. However, it is possible to adopt a more conservative definition of the residual force. For example, a strategy that is oriented to stability could adopt an opposite approach, in which the damping is limited as follows:

$$\alpha_{MAX} = \sqrt{\frac{\mathbf{f}_{MAX}^T \mathbf{f}_{MAX}}{\mathbf{v}^T W^T W \mathbf{v}}} \tag{7}$$

Then, since the maximum displayable force is always $\mathbf{f}_{MAX}$, the following condition must always be satisfied:

$$\hat{\mathbf{f}}_d \leq \mathbf{f}_{MAX} - \mathbf{d} \tag{8}$$

In the case of an admittance-based square robot, the formulation is completely symmetrical exchanging forces with velocities and *vice versa*. Thus, defining the maximum displayable velocity vector in the task space $\mathbf{v}_{MAX}$ according to the maximum velocity vector in the joint space $\dot{\mathbf{q}}_{MAX}$ and the residual displayable velocity $\mathbf{v}_{res}$, it is easy to obtain the maximum damping for an admittance-based *PC*:

$$\begin{cases} \mathbf{v}_{MAX} = J\dot{\mathbf{q}}_{MAX} \\ \mathbf{v}_{res} = \mathbf{v}_{MAX} - \hat{\mathbf{v}}_d \\ ||\beta W \mathbf{f}|| \leq ||\mathbf{v}_{res}|| \Rightarrow \ \beta_{MAX} = \sqrt{\dfrac{(\mathbf{v}_{MAX} - \hat{\mathbf{v}}_d)^T(\mathbf{v}_{MAX} - \hat{\mathbf{v}}_d)}{\mathbf{f}^T W^T W \mathbf{f}}} \end{cases} \tag{9}$$

where β represents the damping of the *PC* in the admittance configuration.

III. EXPERIMENTS

The theoretical expectations of the proposed algorithms has been tested experimentally. Since the paper focuses on proposing an innovative limitation for the *PC* action, we will consider the case of stabilizing a haptic interface interacting with a virtual environment (that is the first application proposed for the *TDPA* [7]). The limitations are anyway applicable in any application in which a *PC* is required, such as teleoperation. In the experiment, one user interacts with a virtual wall by means of a haptic device. The virtual wall is modeled as a first order mechanical impedance:

$$f_w = k(z_P - z_0) - b\dot{z} \tag{10}$$

with $k > 0$ and $b < 0$. This latter condition makes the system unstable, and the instability is handled by means of a passivity observer and a passivity controller, implemented as described in section II. In the implementation of the *PO* and the *PC*, α_{MAX} was maximized either as proposed in 4, or as proposed in 6. The limitation obtained from solving a *QP* problem was not taken into account because of its inherent computational burden, preferring the most diffused methods.

A. Experimental Setup

For implementation simplicity, without loss of generality, we used a 3 DoFs parallel haptic interface with 3 actuated joints [18]. The haptic interface has a Delta-like kinematics, i.e. three R̲UU legs, where the R̲ joint is actuated. Stiffness and damping of the virtual wall were set as $k = 1200N/m$ and $b = -45Ns/m$ The device is equipped with an embedded controller that runs two loops: the high-level loop runs at $1kHz$, provides gravity compensation and receives joint torque targets and saturates them according to the actuator limits. The low-level loop runs at $5kHz$, receives that actuator torque target and provides the current control. The embedded controller (EC) communicates via high-speed USB (3 Mb/s) with a host PC (CPU Intel i7-3610QM 2.30 GHz, 8GB RAM). Figure 2 shows the experimental setup. This PC runs the high-level controller (HLC) that implements the communication, the virtual wall, the passivity observer and the passivity controller. The HLC implements a geometric torque saturation that preserves the direction of the force at the end effector provided by the *PC*. The HLC frequency varies according to the two case studies. Figure 1 shows the control scheme.

B. Case Studies

The goal of the experiment is to stress the drawbacks of a limitation of α that is purely based on the sampling time. In particular, these are apparent in two cases:

1) Low sampling time and high force/torque actuators
2) High sampling time and low force/torque actuators

The first is the case of a robot that constraints the commanded frequency in a real-time application (e.g. the *Universal Robotics UR5*, whose control frequency limit is $125Hz$ and has been used in teleoperation architectures such as in [19]). In this case, the high sampling time (low frequency) makes α_{MAX} much smaller than what the actuators and the task permit. Therefore, we expect a reduced capacity of the *PC* to handle the energy dissipation needed to passivate the interaction with the virtual wall. The second case occurs for a robot that allows for high-frequency control while featuring limited force/torque capabilities, which is common in teleoperation architectures. In this case, the low sampling time sets α_{MAX} to values that cannot be provided by the actuators. If not properly handled, which is what we propose, this makes the *PO* wrongly rely on a complete dissipation of the energy E_{PC}, thus increasing the risk of instability.

These cases have been tested as follows. In case 1 the HLC runs at $200Hz$ and the actuator limits are set to $\tau_{MAX} = 1.48\ Nm$. In the second case, the HLC runs at $1000Hz$ and the

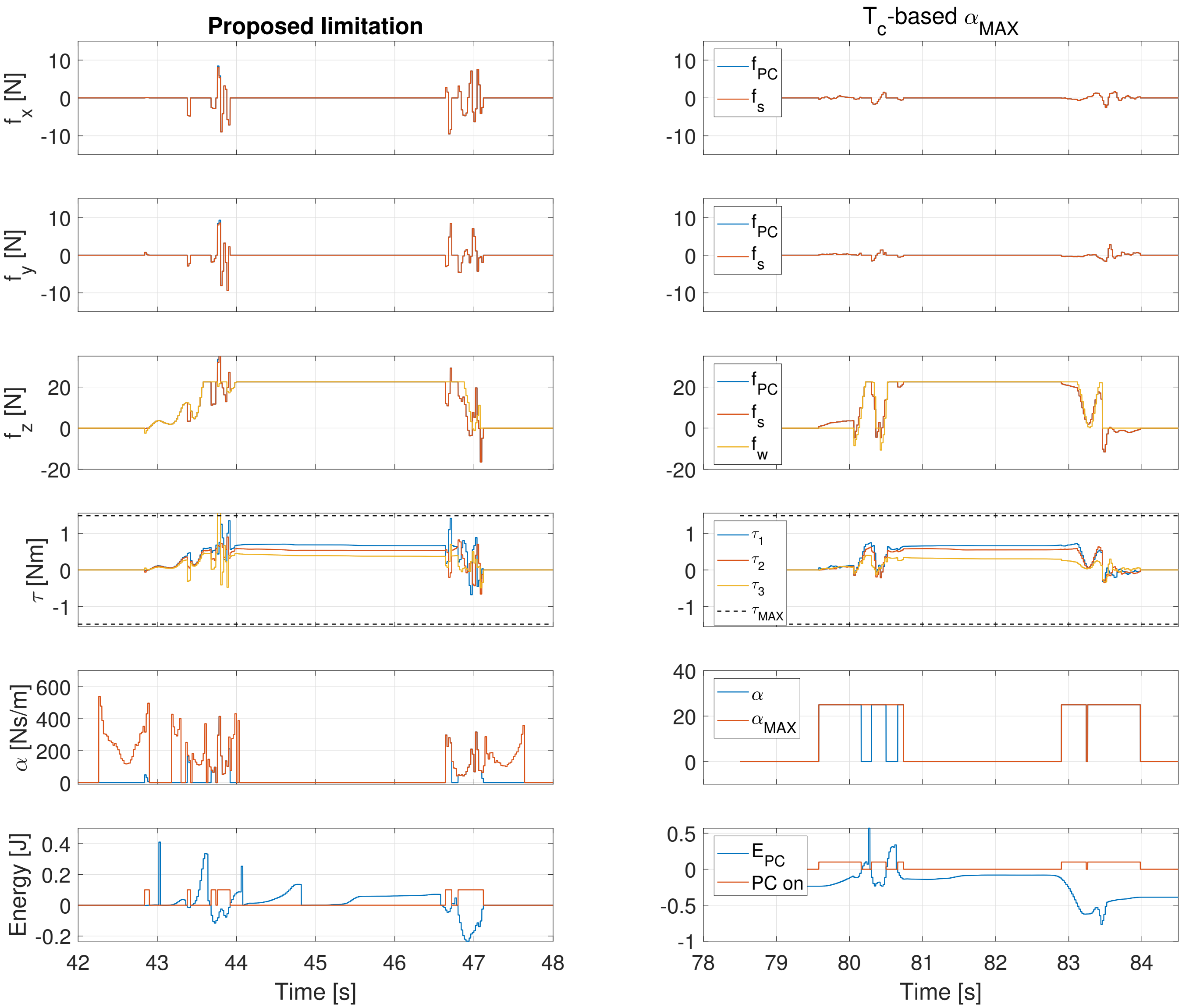

Fig. 3: Experimental results for the first case study. Force components are expressed in the base frame shown in Figure 2. Torque τ_i is the target of the i-th actuated joint in the EC. It is straightforward to see that the tightened limitation of the T_c-based approach produces reference torques much lower than the displayable ones, resulting in fewer dissipation capabilities than physically possible, and then in instability.

actuator limits are set to $\tau_{MAX} = 0.49\ Nm$. In both cases one human operator held the end-effector, initially placed above the virtual wall. The volunteer then penetrated the virtual wall vertically, remaining in contact for 2-3 seconds, then exited the wall.

C. Performance Metrics

The performance of the limitations has been assessed qualitatively by inspecting the forces rendered to the user, the corresponding joint torques, the damping α against its possible maximum value α_{MAX}, and the energy to be dissipated by the PC (i.e. E_{PC}). For the second case, we define an energy dissipation score η_{PC}, that is the percentage of energy E_{PC} that has been dissipated after the saturation due to the actuator limits. At one time sample, said ΔE_{PC} the energy that the PC would dissipate without saturation and $\Delta\tilde{E}_{PC}$ and the energy that is effectively dissipated due to the actuator limits, we define

$$\eta_{PC} = \frac{100}{n_{PC}} \sum_{k \in T_{PC}} \frac{\Delta\tilde{E}_{PC}}{\Delta E_{PC}} \quad 0 \leq \eta_{PC} \leq 100 \tag{11}$$

where T_{PC} is the time interval in which the PC is active and n_{PC} the number if samples in such interval. $\eta_{PC} = 100$ is the best score and means all the energy prescribed by the PC has been dissipated.

IV. RESULTS

The results of the experiment are shown in figures 3 and 4, representative of case studies 1 and 2 respectively. For clarity of representation, only one wall penetration cycle

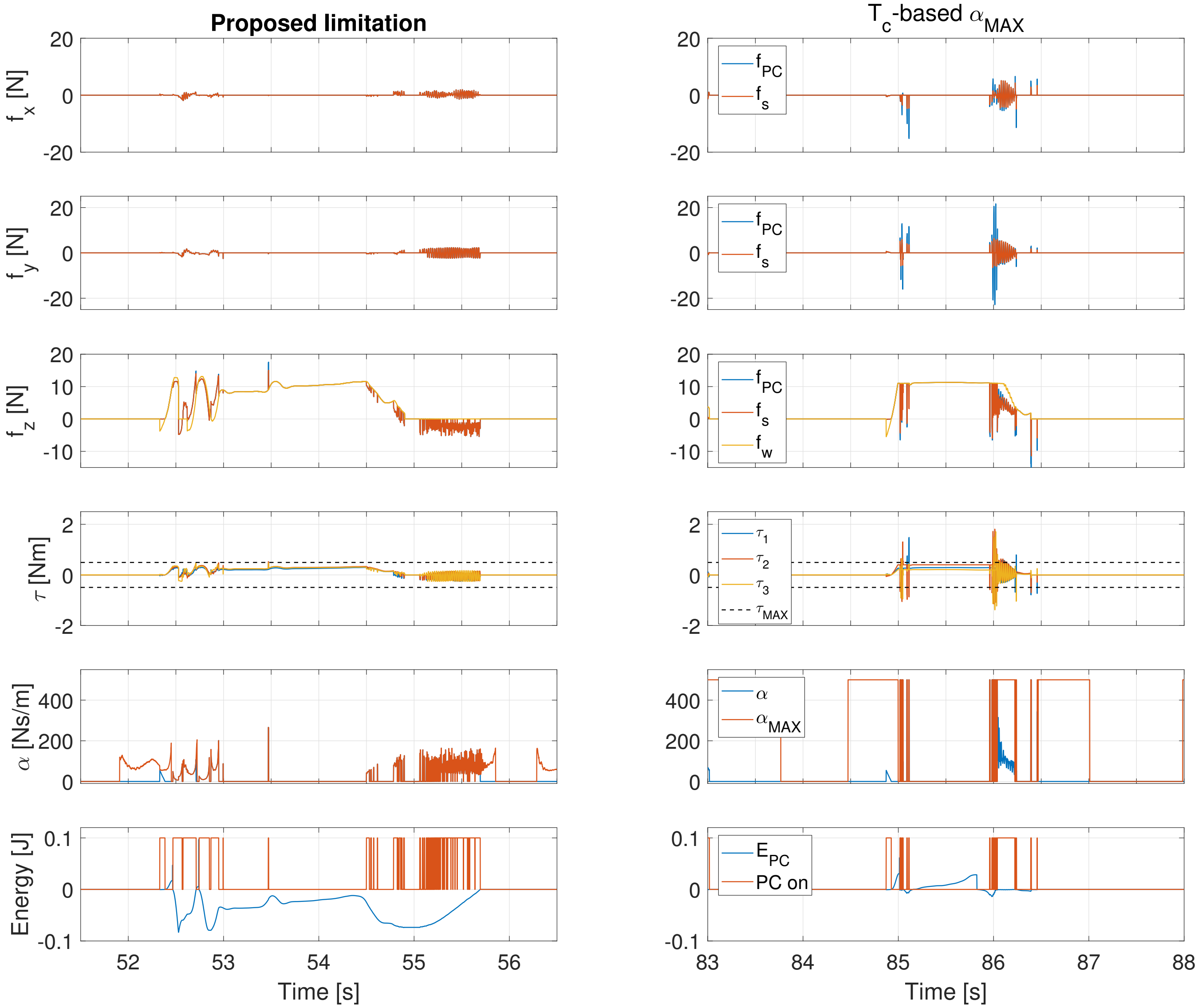

Fig. 4: Experimental results for the second case study. Again, force components are expressed in the base frame shown in Figure 2 and torque τ_i is the target of the i-th actuated joint in the EC. It is evident that the torques produced by the T_c-based approach are upper the physical limits of the system due to the strategy, thus it results in ensuring that more energy is dissipated than it really is. Moreover, since the observed energy is assumed to be dissipated, no more energy is collected to be dissipated in the next steps. Conversely, the proposed approach manages both points.

is represented. Both panels include force components in the base frame (represented in Figure 2) in the first three rows. Saturated force f_s is plotted against the rendered force after the passivation f_{PC} and against the force due to the interaction with the wall f_w. The fourth row reports the torques at the three actuated joints of the interface due to f_{PC} and their limits. The fifth row reports the values of α and α_{MAX} during the interaction, whereas the last row shows E_{PC} and a marker of the activity of the *PC* (the *PC* is active when "PC on" is up). In both figures the first column is obtained with the proposed limitation strategy, whereas the in the second column α_{MAX} is calculated according to 4.

Independently of the limitation strategy and the case study, the penetration of the wall causes instability in the system due to the active nature of the wall ($b < 0$). If a stable contact is achieved (i.e. $\dot{z} \approx 0$) the system does not need passivation. A new unstable condition occurs at the exit of the wall. This behaviour is apparent by looking at the force and E_{PC} plots.

In case 1, it is apparent how the limitation constrained to the sample time limits the possibility of passivation even when actuators allow for stronger actions. With the proposed passivation, $\alpha > 25Nm/s$ whenever the PC is active, with a maximum of 413 Ns/m. This makes a few samples (120 on average in the interval) sufficient to passivate the system whenever $E_{PC} < 0$. Conversely, the sampling-time-based approach requires a longer activity of the *PC* (average of 384 samples) to passivate the system. At the exit of the wall (between 83 and 84 s) the *PC* fails at dissipating all the required E_{PC}. In this case, the human needs to actively contribute to the stabilization of the system. The margin available to the *PC* to exert a stronger passivation action is evident in the torque plots. With the proposed strategy, the required joint torques reach (even overcome) the actuator limits. Conversely, despite the interaction with the wall these torques are less than the maximum value when applying the limitation based on the sample time strategy.

In case 2, the limitation based on sampling time allows for high values of α thus causing joint torques to exceed the actuator limits. It is evident in the force plots, where the force required in the horizontal plane is often saturated. Therefore, the force in output from the *PC* is sufficient to dissipate E_{PC}, but the saturation due to the actuator limits the dissipation of the *PC*, which cannot guarantee passivity. In this case, the score achieved with this dissipation strategy is $\eta_{PC} = 85.4$. The proposed strategy makes joint torques always within the limits permitted by the actuators. However, this limitation does not allow the *PC* to dissipate all the energy E_{PC} in a short time. Therefore, the *PC* requires much time to passivate the system, as it is apparent in the exit phase (54.5 to 55.7 s), or passivation is not achieved, as in the entry phase. Anyway, the *PO* returns always the correct energy to be dissipated, as shown by the energy dissipation score $\eta_{PC} = 99.8$.

V. DISCUSSION AND CONCLUSIONS

In this paper, a new *PC* damping element limiting strategy was presented according to the system's physical capabilities. In the proposed approach, power-limited actuators along with robot configuration were taken into account. Differently from state-of-the-art QP methods, our strategy is expressed in a closed form greatly relieving the computation. We also deal with the problem that rendering torque decreases the maximum action achievable by the *PC*.

The results clearly show the improvements of the proposed limitation with respect to the currently used methods. In fact, in the first case study, the proposed approach allows for better dissipation. In case two, currently used approaches could mistakenly stop passivating considering the system as stable. Conversely, our approach correctly accumulates the energy for the following steps until complete dissipation while respecting the physical limits of the actuators.

The approach is greatly promising. However, some limitations may occur. In particular, the constraint on the damping is scalar and in some situations, this may produce a wrong condition for an *n-DoFs* system (e.g. the limit situation in which only one degree of freedom is working). A conservative solution to this point would be to divide the computed α_{MAX} by a $\sqrt{n}$ factor, but this situation is practically unachievable. Conversely, a concrete problem is represented by devices with *n-DoFs* in which the actuators are characterized by different power limits. The bigger are these differences, the worse this approach will work. However, for many of famous haptic interfaces (such as *Omega X*, *Omega 6* and *Falcon*) actuators are identical over all *DoFs*.

In future works, we plan to adopt this limitation on teleoperation architectures beyond working on a solution to the limitations of this approach.

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