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# Elasto-Plastic Robot Compliance for Safe and Robust Teleoperation

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## I. Introduction

Teleoperation with communication delay comes along with a multitude of challenges. Besides stability which can be guaranteed via energy-based control methods [1], among others, further safety risks result from delayed perception of the human operator, for instance. The method proposed in [1] helped to limit impacts of a teleoperated robot on obstacles, that were not perceived by the operator yet, through reduction of the robot compliance. Still, such critical contacts were only prevented when resulting from a robot motion commanded by the teleoperator. In contrast, when an object such as another robot moved against the teleoperated robot, that remained stiff, potentially putting the systems at risk.

For that sake, we developed the elasto-plastic robot compliance (EPRC, [2]). This approach observes the activity of the robot's environment and triggers a plastic, evasive motion whenever an active environment is recognized (the robot motion does not result from the teleoperator's command).

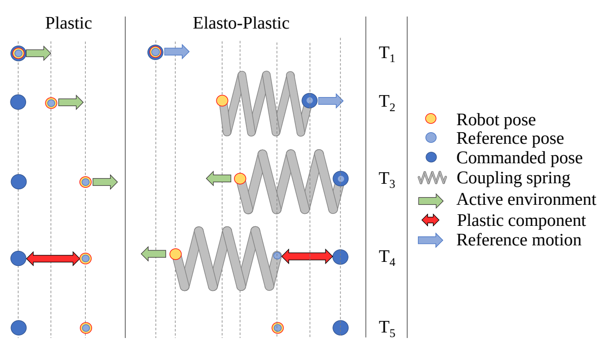


Fig. 1. Virtual Elastic Robot Compliance.

The control logic of the plastic reaction is visualized in Fig. 1: When a robot motion results from an active environment, the reference pose of the robot is updated with this motion such that the spring of the impedance controller between reference ${}^{W}H_{R'}$ and robot pose ${}^{W}H_{R}$ is not deflected. In contrast, if the environment is passive, the reference motion follows the pose ${}^{W}H_{ED^*}$ commanded by the human teleoperator analogous to conventional impedance control coupling. Thus, the method enables unrestricted robot interactions with passive environments while enabling extraordinary compliance in case of interactions with active environments. The EPRC has already been validated in a teleoperation scenario involving an astronaut aboard the International Space Station [2] and in a Caritas healthcare facility [2]. In teleoperation, the EPRC acts as a local autonomous support on the robot side [4] which is particularly beneficial in case of high communication delay [1]. In this work-in-progress, we present initial results on application of EPRC in autonomous robots and evaluate the coupling performance under EPRC when applied on two physically connected robots during teleoperation.

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## II. Implementation

In contrast to comparable approaches [3], here, the active environment is recognized based on power observation $P(t)$=$v(t)F(t)$ requiring no force-torque sensors at the robot's end-effector. Regarding the sign of the power, the flow direction can be analysed (left-to-right direction $L2R$, right-to-left direction $R2L$):

$$P_{\mathrm{L2R}}(t) = \begin{cases} -P(t) & \text{, if } P(t) < 0 \\ 0 & \text{, if } P(t) \geq 0, \end{cases} \tag{1}$$

$$P_{\mathrm{R2L}}(t) = \begin{cases} P(t) & \text{, if } P(t) > 0 \\ 0 & \text{, if } P(t) \leq 0. \end{cases} \tag{2}$$

If a power flows from environment to the controller ($P^{env}_{R2L} > 0$), an active environment is accounted as described in [2], such that $\nu$ is set to one, if a power threshold $P_{thr}$ is overcome:

$$\nu(t) = \begin{cases} 1 & \text{, if } P^{env}_{R2L}(t) > P_{thr} \\ 0 & \text{, else.} \end{cases} \tag{3}$$

The plastic, evasive action of the robot is achieved by integrating the robot motion $v^R$ caused by the active environment onto the robot reference pose $x^{R'}$ whenever an active environment is recognized ($\nu = 1$):

$$x^{R'}(t) = x^R(t_0) + T_s \sum_{0}^{t} (v^{R^*}(\tau) + \nu(\tau) v^R(\tau)), \tag{4}$$

with the motion $v^{R^*}$ commanded to the robot. The EPRC can be easily integrated into arbitrary impedance controllers since it is purely based on the robot velocity and the force computed by the impedance controller. Thereby, the approach is independent of models or force-torque sensors at the end-effector, provides seamless role transition, and enables role distribution specific for each degree-of-freedom.

## III. Evaluation

Earlier work [2] has shown that the EPRC is not only meaningful to provide safety in teleoperation at high delay, but also relevant at low delay scenarios independent of teleoperation aspects. The EPRC is able to detect a human in the environment without visual sensors or models of the environment. For example, when the robot interacts with a door at the same time as a human (compare Fig. 2), the human's activity can be detected in a power-based manner such that the robot can be put into a subordinate role via EPRC. Thus, the EPRC is capable to fulfill challenging norms and standards for human-robot shared environments requiring that a robot has to be able to detect a human which is challenging due to unknown door dynamics and a potential opacity of the door.

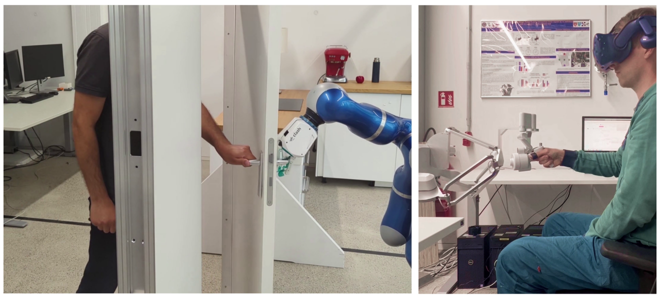

Fig. 2. Safety in Human-Robot Shared Environments.

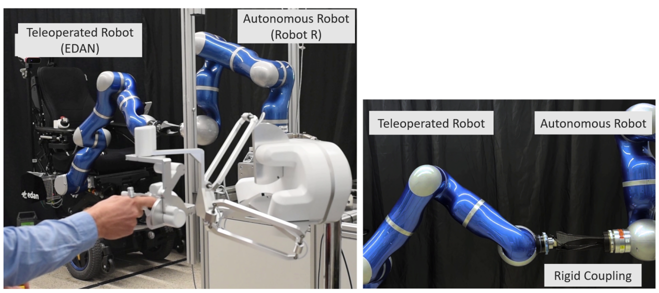


Fig. 3. Seamless Role Transitions in Cooperation of Teleoperated and Autonomous Robots.

The experiments presented in Fig. 4 and Fig. 5 provide the first proof that the robustness of EPRC is maintained when installed on two cooperating robots. The two robots are tightly physically connected (compare Fig. 3), representing the most challenging situation for two cooperative robots, which can be alleviated by EPRC. First (compare Fig. 4), the left robot EDAN is teleoperated (command ${}^{W}H_{ED^*}$) and robot R follows the motion due to the first condition in (3) such that ${}^{W}H_{R'}$=${}^{W}H_R$. Although EPRC is enabled also on EDAN, the motion of robot R does not trigger plastic motions of EDAN: commanded ${}^{W}H_{ED'}$ equals reference pose ${}^{W}H_{ED^*}$ and $\nu$=0. The second experiment shows, for the first time, that the EPRC is functional with autonomous systems: The robot R performs autonomous sinusoidal motions $t$=$[220s, 248s]$. As the source of activity, it triggers plastic reactions of EDAN: robot pose ${}^{W}H_{ED}$=${}^{W}H_{ED'}$, while ${}^{W}H_{ED^*}$=0. From $t$=248$s$, EDAN is teleoperated. Thereby, the operator partially supports (for instance $t$=$[257s, 260s]$) or counteracts (for instance $t$=$[297s, 298s]$) the sinusoidal motion of robot R.

## IV. Discussion and Conclusion

The experiment confirmed that the coupling rigidity of two physically connected robots is maintained if EPRC is enabled

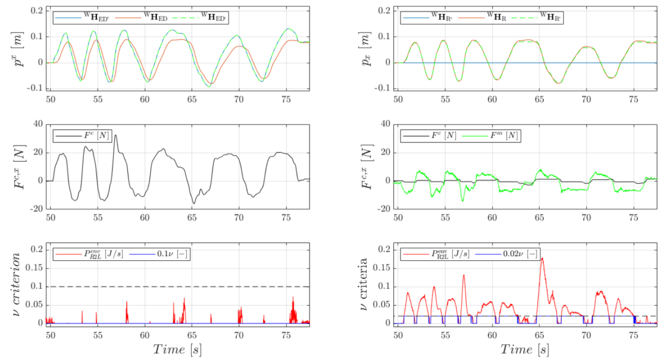

Fig. 4. Exp. 1 - Robot R is steady until EDAN is teleoperated such that robot R reacts plastically.

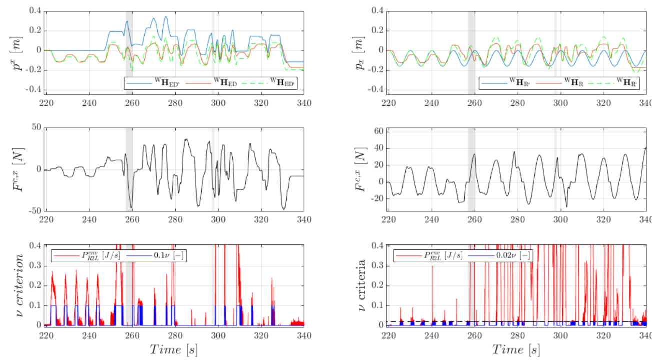

Fig. 5. Exp. 2 - EDAN is teleoperated ($t$ = 250$s$), while robot R performs autonomous sinusoidal motions.

on both robots. Still, it should be noted that a conservative controller tuning was chosen for safety reasons in this early stage of evaluation. Increasing controller stiffness and reducing power thresholds and damping will further enhance the coupling performance.

Owing to the model-free functionality and the unnecessity of force sensing, the EPRC is directly applicable to a large variety of setups and scenarios. Future work has to focus on the integration in more complex autonomous settings, requiring the consideration of the intentionally induced plastic position drift.

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