Elasto-Plastic Robot Compliance in Human-Robot Interaction and Robot-Robot Cooperation

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Abstract—Efficient Human-Robot Interaction requires flexible role switching and robust role distribution. Leader and follower agents are mostly recognized based on interaction forces. This often comes with the drawback of reduced robustness and the necessity of models of the robot's environment or human behaviour. This video presents the recently proposed Elasto-Plastic Robot Compliance (EPRC) concept that, being power-based, additionally considers the robot velocity in role recognition. Thus, active environments can be detected inducing enhanced virtual plastic compliance of the robot. Such plastic compliance refers to evasive robot motions induced specifically by active environments, after which the robot is not pushed back to the initial point of contact in contrast to elastic compliance. The video further presents advantages as role distribution specific to different degrees-of-freedom, independence from model generation and unrestricted force application.

Index Terms—laboratory experiments, collaborative interaction, HCI theory, concepts and models.

I. INTRODUCTION

Human Robot Interaction (HRI) and Robot Cooperation comes along with a multitude of challenges when it comes to universally applicable solutions. Besides compliance control, a major challenge in HRI is an adaptive distribution of roles to the agents with continuous transitions between roles. A variety of human-like strategies for leader-follower distribution have been proposed in literature [1]–[6]. Proposed solutions for detecting leader and follower roles of agents are based on applied interaction forces [1], [3], [7], reinforcement learning [1] or task performance [2]. Such approaches often suffer from limited interaction forces, model dependency, complexity and applicability to highly specific scenarios. Especially, haptic interaction has been shown to be crucial for sensory-motor coordination in collaborative settings [5].

In [8], [9], we introduced the power-based elasto-plastic robot compliance (EPRC) concept to alleviate such restrictions. The EPRC approach detects active environments and triggers a virtual plastic reaction in case of externally induced robot motion.

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 (DoF). Thus, the approach is particularly beneficial in dynamic human-robot shared environments (compare Fig. 1) which are hard to model.

Current norms prevent a robot from handling a door, since the robot has to be able to detect a human visually or via force sensors which is challenging due to unknown door dynamics and a potential opacity of the door. Here, the EPRC detecting a robot motion induced by the human, is able to trigger an evasive motion of the robot, putting the robot into a subordinate role. Thereby, the robot evades the human motion without requiring models of the environment or of the human behaviour. Since the EPRC is power-based, the robot is still able to apply unrestricted forces against its environment if desired.

Fig. 1. Safety in Human-Robot Shared Environments.

The EPRC has already been validated in a teleoperation scenario [10], [11] involving an astronaut aboard the International Space Station [8], [12] and in a Caritas healthcare facility [8]. In teleoperation, the EPRC acts as a local autonomous support on the robot side [13] which is particularly beneficial in case of high communication delay [11].

II. CONCEPT AND FUNDAMENTALS

Most advanced robot controllers are based on virtual elastic springs pushing the robot to the desired pose as visualized in Fig. 2. The red dot represents the robot pose, the blue dot the reference pose and the green dot the pose commanded via an input device.

The EPRC aims for unrestricted robot performance in passive environments while enabling extraordinary compliance in case of interactions with active environments. The active environment is recognized based on power observation $P(t) = v(t)F(t)$ requiring no force-torque sensors at the robot's
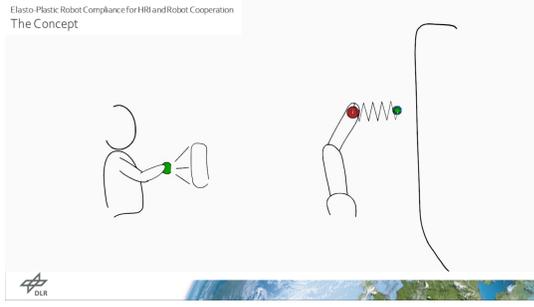
Fig. 2. Virtual Elastic Robot Compliance.

end-effector. Regarding the sign of the power, the flow direction can be analysed (left-to-right direction $L2R$, right-to-left direction $R2L$):

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

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

If a power flows from environment to the controller ($P_{L2R}^{env} > 0$), an active environment is accounted as described in [8], such that ν is set to one:

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

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 $v^{R'}$ whenever an active environment is recognized ($\nu = 1$, [8]):

$$x^{R'}(t) = x^R(t_0) + T_s \sum_0^t (v^{R^*}(\tau) + \nu(\tau)v^R(\tau)), \quad (4)$$

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. As an effect of the plastic kind of the compliance, the robot is not pushed back to the initial point of contact with the active environment in contrast to elastic compliance involving virtual springs.

III. RESULTS

The video confirms the EPRC functionality in human-robot shared environments (compare Fig. 1). While the teleoperating human closes the door, a human pushes the robot from the other side such that the EPRC detects an active environment and evades the motion. When the environment has turned passive again, the robot is able to apply forces and close the door.

It has to be noted that the capability of seamless role transition enabled by the EPRC allows the active environment to plastically move the robot even during arbitrary spring deflection. That means, even if the robot presses against the environment with arbitrary force, a human can touch and move the robot plastically as long as it overcomes the

force applied by the robot (compare video section of Fig. 3). This continuous switching of roles results in a human-like interaction behaviour.
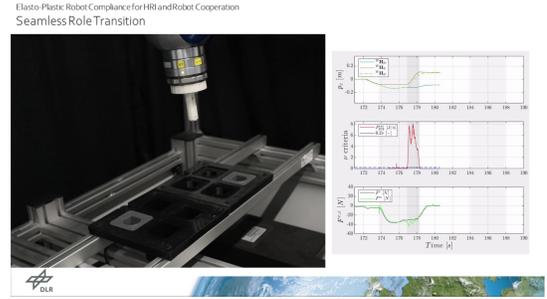

Fig. 3. Seamless Role Transition.

Since energy observation and control can act in each DoF separately in EPRC, the robot can have different roles in different DoF. In Fig. 4, the robot pushes against the environment in z-direction, but the active environment (here represented by the left hand of the teleoperating human) can easily push the robot plastically in perpendicular directions.

Fig. 4. DoF-specific Role Distribution.

Although the role transition is particularly reactive, the distribution of roles is highly robust. Analogous to humans, the robot is able to combine plastic reactions and elastic reactions independent of the history of interactions. The video (compare video section of Fig. 5) aims to underline that the robot behaves as expected during spontaneous interactions and does not require resets or discrete switching of roles.

Fig. 5. Robustness of Role Distribution.

Analogous to human-robot shared environments, the EPRC can be straight-forward applied to robot-robot cooperation. In the respective part of the video (compare Fig. 6), both robots are EPRC controlled confirming the extraordinary robustness of the EPRC method. While the right robot follows a pre-designed velocity profile, the left robot complies with the resulting active environment (right robot arm). Again, EPRC enables different roles in different degrees of freedom for both robots. Note that for more sophisticated autonomous agents, the plastic position drift intentionally introduced by EPRC has to be accounted in trajectory generation.
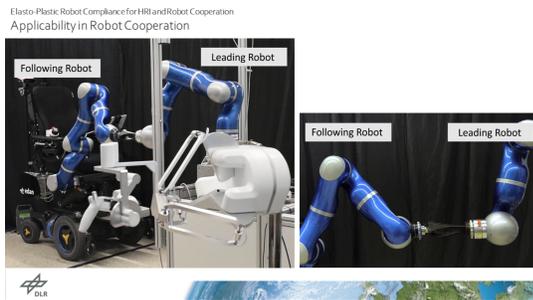

Fig. 6. Applicability in Robot Cooperation.

Since both robots are equipped with EPRC control, the left robot can overtake a leading role at any time. The video presents a teleoperation scenario with two EPRC controlled robots (compare Fig. 7). The left robot is teleoperated while the right robot tries to continue following the pre-designed velocity profile. Depending on the behaviour of the teleoperated robot, both robots switch their role as soon as the interaction force of the left robot overcomes the one of the autonomous right robot. Again, the resulting seamless role transition is comparable to human-human interaction behaviour.
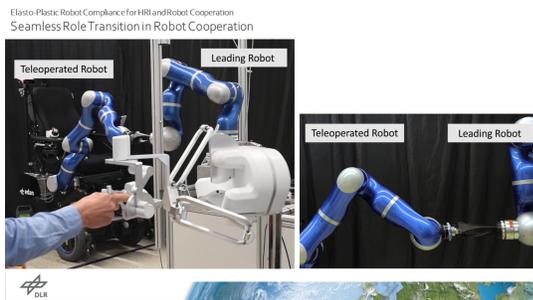

Fig. 7. Seamless Role Transition in Robot Cooperation.

IV. CONCLUSION

The video highlights the aptitude of EPRC for HRI and robot collaboration. In contrast to comparable approaches, the EPRC allows for human-like seamless role transition. While providing high reactiveness, the approach requires neither force-torque sensing at the end-effector, models of human behaviour or the environment, nor conservative force limitation. A collaboration scenario with two EPRC controlled robots confirmed the extraordinary robustness of the EPRC. Thanks to the model-free functionality, the EPRC is directly applicable to a large variety of scenarios. Still, future work has to focus on the integration in autonomous settings requiring the consideration of the intentionally induced plastic position drift.

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