Editorial
Variable Impedance Control and Learning in Complex Interaction Scenarios: Challenges and Opportunities

I. Introduction

DAY by day, robots are expected to enter various application scenarios and interact with unknown and dynamically changing environments. More specifically, we are expecting robots to be out from their caged industrial workspace and operate among us in our dynamic and uncertain environments. To have robots safely and robustly interacting with their surroundings and cooperating with people, they must present some degree of mechanical compliance. While such compliance can be achieved passively, using elastic and flexible elements in the robot's mechanical design, control algorithms are able to shape the robot's mechanical compliance (e.g., stiffness, damping, and inertia) in a much more versatile manner. A well-known approach to control physical interaction is via impedance control, where it is possible to control the robot's mechanical impedance (i.e., the dynamic relation between force and velocity) at a given interaction point. In this context, there are several fundamental research problems to address, such as

- How to design control systems that have to work with potentially uncertain environment models and uncertain sensory feedback?
- How to deal in real-time with unpredictable and complex interactions?

To cope with such uncertain physical interactions, it is possible to use Variable Impedance Control (VIC) as a feasible solution to overcome position uncertainties and subsequently avoid large impact forces, since robots are controlled to modulate their motion or compliance according to force perception. However, knowing what the desired robot impedance should be for a given scenario is still an open question. Thus, two main research questions arise in VIC:

- How can robots perform complex physical interaction tasks while avoiding hard-coding?
- How can robots acquire knowledge and use it to perform such tasks intelligently?

In this direction, machine learning has been providing suitable tools to learn VIC skills, e.g., from human demonstrations or through robot's self exploration.

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The special issue on *Variable Impedance Control and Learning in Complex Interaction Scenarios: Challenges and Opportunities* published by IEEE Robotics and Automation Letters is dedicated to addressing the challenges mentioned above. To push the next achievements in this area, we need to endow robots with control and intelligent algorithms that augment their capabilities to acquire knowledge autonomously and use it while interacting with the world around them; enforcing safety, efficiency, and reliability. This article, authored by the Guest Editors of the Special Issue, serves as an introduction to it. The Guest Editors were also the organizers of two workshops that motivated this Special Issue: "Workshop on Variable Impedance Robot Skills: Control & Learning" [A1] and "Workshop on Variable Impedance Robotics Skills: Challenges and Opportunities" [A2] both organized in conjunction with the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) in 2018 and 2021, respectively. The first workshop, held on-site, included talks from 8 invited speakers and 4 contributed extended abstracts, with more than 70 attendees. The second workshop, held virtually, included presentations from 9 invited speakers and 3 accepted extended abstracts, with over 75 participants in the live session. Such workshops reflect a wide interest in the topic from the robotics community. In 2020, two of the guest editors also published a survey on the topic [A3]. Nine letters that report the latest advances in Variable Impedance Learning & Control (VILC) were selected for the Special Issue after the review process. These papers focus on different aspects of the topic, as summarized in the following section.

II. Guide to the Special Issue

Physical human-robot interaction: Learning from Demonstration (LfD) has been widely studied as a convenient way to transfer human skills to robots. This learning approach is aimed at extracting relevant motion patterns from human demonstrations and subsequently applying these patterns to different situations. In this vein, Caldarelli et al. [A4] proposed a novel, force-based LfD algorithm for inferring time-varying stiffness profiles, leveraging the relationship between stiffness and tracking error, and involving human-robot interaction. Gaussian process regression is used by the robotic system to execute a perturbed reference trajectory obtained from the demonstrations. During the execution, if the manipulator deviates from its expected behavior due to perturbations, human correct the robot by intervening the execution. These interventions are measured and used to infer the desired control stiffness.

Contact-rich manipulation: Reinforcement Learning (RL) is a widely studied topic in the learning and control communities, it has a promising framework to automatically learn control parameters of a wide variety of tasks. Yang et al. [A5] proposed an approach to deal with the problem of learning contact rich manipulation policies by extending an existing skill-based RL framework with a VIC action space. Specifically, they leveraged a framework for learning latent action spaces for RL agents from demonstrated trajectories and integrate it with a variable impedance Cartesian space controller by incorporating VIC into the action space of this RL framework.

Aerial physical interaction: Physical interaction with uncertain environments is a challenging task that demands for good tracking performance while ensuring a safe interaction. The problem is even more challenging when the robot is an unmanned aerial vehicle. Benzi et al. [A6] present an effective approach for physical aerial interaction with uncertain and dynamic environments. Their control framework is based on a time-varying impedance controller that exploits energy tanks to guarantee stable interactions. Tank parameters are adapted online to make the proper amount of energy available to accurately execute the task. Zhang et al. [A7] focuses on contact-based inspection applications, where a tilt-arm omnidirectional flying vehicle is capable to slide an end-effector along different surfaces. Using proprioceptive and tactile sensing, the gains of the impedance controller are set in real-time using a neural network so that the system remains robust against different environment properties and shapes.

Soft and flexible robots: Articulated soft robots, i.e., robots with flexible joints and rigid links, have a non-linear force-deflection dependency and intrinsic flexibility which significantly complicate their robust control. Pedone et al. [A8] exploit an input-state observer to estimate the torque difference arising from an approximate robot model and develop a robust control technique that compensates for the estimated inaccuracy and allows the decoupled control of joint position and stiffness. Harder et al. [A9] present and evaluate a passivity-based controller that can achieve high-precision link-side trajectory tracking while simultaneously controlling joint compliance for biologically inspired, bidirectional variable-stiffness actuators.

Medical and healthcare robotics: Robots are reshaping the future of medicine by advancing diagnostics, treatments, and services to improve patient health. For instance, scoliosis assessment is made by an expert medical practitioner that slides with a certain contact force an ultrasound imaging probe along the patient's back. Automating this process requires precise control of the motion of the probe as well as of the interaction forces. Duan et al. [A10] formulate the scoliosis assessment as a quadratic optimization problem and exploit learning techniques to generate suitable motion and impedance profiles from expert demonstrations.

Wearable robotics: Managing safe and effective physical interaction with humans is critical for wearable robotic systems such as assistive exoskeletons and prostheses. Liu et al. [A11] introduce a novel method of personalizing the impedance controller of the knee joint in a robotic lower limb prosthesis using bilevel optimization facilitated by inverse reinforcement learning to produce normative knee kinematics. Nalam et al. [A12] examined how humans modulate their ankle stiffness in response to varying ground compliance to inform the development of safe and effective lower extremity robots.

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Appendix
Related Articles

[A1] F. J. Abu-Dakka, M. Abderrahim, D. Lee, and R. Ikeura, "Workshop on variable impedance robot skills: Control & learning," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2018. [Online]. Available: https://iros18wsimpedance.weebly.com/
[A2] F. J. Abu-Dakka, M. Saveriano, J. Bohg, and M. Hoffmann, "Workshop on variable impedance robotics skills: Challenges and opportunities," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2021. [Online]. Available: https://sites.google.com/view/vilc-iros2021
[A3] F. J. Abu-Dakka and M. Saveriano, "Variable impedance control and learning – A review," *Front. Robot. AI*, vol. 7, 2020, Art. no. 590681.

[A4] E. Caldarelli, A. Colomé, and C. Torras, "Perturbation-based stiffness inference in variable impedance control," *IEEE Robot. Automat. Lett.*, vol. 7, no. 4, pp. 8823–8830, Oct. 2022.

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[A6] F. Benzi, M. Brunner, M. Tognon, C. Secchi, and R. Siegwart, "Adaptive tank-based control for aerial physical interaction with uncertain dynamic environments using energy-task estimation," *IEEE Robot. Automat. Lett.*, vol. 7, no. 4, pp. 9129–9136, Oct. 2022.

[A7] W. Zhang, L. Ott, M. Tognon, and R. Siegwart, "Learning variable impedance control for aerial sliding on uneven heterogeneous surfaces by proprioceptive and tactile sensing," *IEEE Robot. Automat. Lett.*, vol. 7, no. 4, pp. 11275–11282, Oct. 2022.

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[A9] M. Harder, M. Keppler, X. Meng, C. Ott, H. Höppner, and A. Dietrich, "Simultaneous motion tracking and joint stiffness control of bidirectional antagonistic variable-stiffness actuators," *IEEE Robot. Automat. Lett.*, vol. 7, no. 3, pp. 6614–6621, Jul. 2022.

[A10] A. Duan, M. Victorova, J. Zhao, Y. Sun, Y. Zheng, and D. Navarro-Alarcon, "Ultrasound-guided assistive robots for scoliosis assessment with optimization-based control and variable impedance," *IEEE Robot. Automat. Lett.*, vol. 7, no. 3, pp. 8106–8113, Jul. 2022.

[A11] W. Liu, R. Wu, J. Si, and H. Huang, "A new robotic knee impedance control parameter optimization method facilitated by inverse reinforcement learning," *IEEE Robot. Automat. Lett.*, vol. 7, no. 4, pp. 10882–10889, Oct. 2022.

[A12] V. Nalam, C. Bliss, J. B. Russell, O. Save, and H. Lee, "Understanding modulation of ankle stiffness during stance phase of walking on different ground surfaces," *IEEE Robot. Automat. Lett.*, vol. 7, no. 4, pp. 9294–9301, Oct. 2022.