

A Software Ecosystem for Research in Reinforcement Learning-based Receding Horizon Control

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Abstract—Robotics research in locomotion is undergoing a transformative shift towards the use of learning-based tools. Despite being shown to be capable of remarkable robustness and performance even when applied to real-world environments, some key inherent limitations such as safety guarantees, interpretability, sample efficiency, persist. For this reason, it is the authors’ belief that more classical control approaches should not be disregarded yet. We thus advocate for a hybrid approach, combining offline data-based policy design, specifically through Reinforcement Learning (RL), with classical online Motion Planning, i.e. Receding Horizon Control (RHC). Even though this kind of hybrid approaches are not entirely new, to the authors’ knowledge, there is no specific tool currently available for research in this domain. To this purpose, we developed a modular software ecosystem, hereby briefly presented in its main components and features. To facilitate its usability and diffusion, we made all the core components open source under the GPLv2 license. Furthermore, to showcase the potential of our framework and approach, we briefly present a proof-of-concept example combining a high-level RL agent coupled with a lower-level MPC controller for the execution of a simple locomotion task on a simulated quadruped robot.

I. A BRIEF HISTORICAL OVERVIEW: from Markov Decision Processes and Dynamic Programming to modern Receding Horizon Control and Reinforcement Learning

State-of-the-art of locomotion and manipulation pipelines have been shown to be capable of remarkable performance and robustness [1]–[4]. These results stand on the shoulders of more than seventy years of research in robotics, control and learning, starting from the very first industrial automated robot *Unimate* in the 1950s [5], Richard Bellman’s pioneering work in the late 1950s and early 1960s on *Markov Decision Processes* (MDPs) [6] and *Dynamic Programming* [7] (DP) and the birth of *Artificial Intelligence* (AI) as an established field of study thanks to the contributions of researchers like Alan Turing, John McCarthy, Marvin Minsky and Claude Shannon. Specifically, the introduction of the so-called *Bellman equation* [7] for the *Value Function* in conjunction with the formulation of MDPs, laid the foundations of DP as a systematic method for solving sequential decision-making problems by breaking them down into simpler sub-problems [7]. Later on, the development of *Policy Iteration* [8], *TD-learning* [9], *Q-learning* [10], the increased popularization of back-propagation [11] as a way of training powerful neural function approximators and the ever-increasing computational resources progressively paved the way to the ancestors of today’s most successful and

employed on-policy and off-policy Reinforcement Learning (RL) algorithms PPO [12] and SAC [13], respectively. Some of these ancestors include, for instance, the *Natural Policy Gradient* [14], *Deep Q-Networks* (DQN) [15], *Deep Deterministic Policy Gradient* (DDPG) [16] and *Trust Region Policy Optimization* [17] algorithms. In an analogous way, DP principles served as a foundational basis for the evolution of modern RHC [18]. Just as DP breaks down complex problems into smaller subproblems and iteratively finds optimal solutions by considering future consequences, RHC iteratively solves finite-horizon optimal control problems over shorter time intervals, considering system dynamics and constraints. Over the years, many algorithms for the solution of receding-horizon nonlinear optimization problems have been developed, and several of them are directly tied to the continuous-time dynamics declination of DP, namely *Differential Dynamic Programming* (DDP) [19]–[22].

II. A HYBRID APPROACH: Learning-Based Receding Horizon Control with Reinforcement Learning

Most of the currently employed control tools and pipelines for locomotion rely either on online “model-based” controllers [3], [18] or “model-free” learned policies (often RL-based and trained offline) [1], [2], [23]–[35], with few exceptions [36]. In the past years there have been several attempts at combining-learning based method and receding horizon controllers, e.g. [37], [38]. Specifically, the following main approaches can be identified [39]:

- 1) *Model augmentation*: integration of learned models into RHC controllers to improve prediction accuracy and control performance [23]–[25].
- 2) *Adaptive tuning and parameter optimization*: RHC parameters tuning (e.g. weights, costs, constraints), based on real-time data [26]–[30].
- 3) *Safety*: a learned-policy is coupled with a RHC controller, which in this context takes the role of a *safety filter* [31]–[35].

Our approach to reinforcement learning-based RHC, which is synthetically depicted in Fig. 1, can be framed as a hybrid between 1) and 2) and it is to some extent complementary to what was done in [39], where a RHC is used to rollout reference motions and footstep plans during the training of a RL tracking policy. Instead of using the RHC controller just for training, we actually aim at hierarchically coupling it with a higher level agent during both training and real-world deployment. This allows to tackle problems which are non-trivial at the RHC level (like phase selection), while also exploiting the robustness and flexibility of the agent, the ability of the controller of ensuring safety and

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controller. Notably, we observe the emergence of completely acyclic contact phases, varying from crawling to bound-like patterns.

REFERENCES

- [1] L. Schneider, J. Frey, T. Miki, and M. Hutter, “Learning risk-aware quadrupedal locomotion using distributional reinforcement learning,” *arXiv preprint arXiv:2309.14246*, 2023.
- [2] T. Miki, J. Lee, L. Wellhausen, and M. Hutter, “Learning to walk in confined spaces using 3d representation,” 2024.
- [3] B. Dynamics, “Atlas Gets a Grip.” https://www.youtube.com/watch?v=e1_QhJ1EhQ, 2023.
- [4] B. Dynamics, “Stepping Up, Reinforcement Learning with Spot.” <https://www.youtube.com/watch?v=Kf9WDqYKYQQ>, 2023.
- [5] M. Xu, J. M. David, S. H. Kim, *et al.*, “The fourth industrial revolution: Opportunities and challenges,” *International journal of financial research*, vol. 9, no. 2, pp. 90–95, 2018.
- [6] R. Bellman, “A markovian decision process,” *Journal of mathematics and mechanics*, pp. 679–684, 1957.
- [7] R. Bellman and R. Kalaba, “Dynamic programming and adaptive processes: mathematical foundation,” *IRE Transactions on Automatic Control*, no. 1, pp. 5–10, 1960.
- [8] R. A. Howard, “Dynamic programming and markov processes,” 1960.
- [9] A. G. Barto, R. S. Sutton, and C. W. Anderson, “Neuronlike adaptive elements that can solve difficult learning control problems,” *IEEE transactions on systems, man, and cybernetics*, no. 5, pp. 834–846, 1983.
- [10] C. J. C. H. Watkins, “Learning from delayed rewards,” 1989.
- [11] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, “Learning representations by back-propagating errors,” *nature*, vol. 323, no. 6088, pp. 533–536, 1986.
- [12] J. Schulman, F. Wolski, P. Dhariwal, A. Radford, and O. Klimov, “Proximal policy optimization algorithms,” *arXiv preprint arXiv:1707.06347*, 2017.
- [13] T. Haarnoja, A. Zhou, P. Abbeel, and S. Levine, “Soft actor-critic: Off-policy maximum entropy deep reinforcement learning with a stochastic actor,” in *International conference on machine learning*, pp. 1861–1870, PMLR, 2018.
- [14] S. M. Kakade, “A natural policy gradient,” *Advances in neural information processing systems*, vol. 14, 2001.
- [15] V. Mnih, K. Kavukcuoglu, D. Silver, A. A. Rusu, J. Veness, M. G. Bellemare, A. Graves, M. Riedmiller, A. K. Fidjeland, G. Ostrovski, *et al.*, “Human-level control through deep reinforcement learning,” *nature*, vol. 518, no. 7540, pp. 529–533, 2015.
- [16] T. P. Lillicrap, J. J. Hunt, A. Pritzel, N. Heess, T. Erez, Y. Tassa, D. Silver, and D. Wierstra, “Continuous control with deep reinforcement learning,” *arXiv preprint arXiv:1509.02971*, 2015.
- [17] J. Schulman, S. Levine, P. Abbeel, M. Jordan, and P. Moritz, “Trust region policy optimization,” in *International conference on machine learning*, pp. 1889–1897, PMLR, 2015.
- [18] R. Grandia, F. Jenelten, S. Yang, F. Farshidian, and M. Hutter, “Perceptive locomotion through nonlinear model-predictive control,” *IEEE Transactions on Robotics*, 2023.
- [19] D. H. Jacobson and D. Q. Mayne, “Differential dynamic programming,” (*No Title*), 1970.
- [20] E. Todorov and W. Li, “A generalized iterative lqg method for locally-optimal feedback control of constrained nonlinear stochastic systems,” in *Proceedings of the 2005, American Control Conference, 2005.*, pp. 300–306, IEEE, 2005.
- [21] M. Diehl, H. J. Ferreau, and N. Haverbeke, “Efficient numerical methods for nonlinear mpc and moving horizon estimation,” *Nonlinear model predictive control: towards new challenging applications*, pp. 391–417, 2009.
- [22] Y. Tassa, T. Erez, and E. Todorov, “Synthesis and stabilization of complex behaviors through online trajectory optimization,” in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4906–4913, IEEE, 2012.
- [23] A. Aswani, H. Gonzalez, S. S. Sastry, and C. Tomlin, “Provably safe and robust learning-based model predictive control,” 2012.
- [24] E. Terzi, L. Fagiano, M. Farina, and R. Scattolini, “Learning multi-step prediction models for receding horizon control,” in *2018 European Control Conference (ECC)*, pp. 1335–1340, IEEE, 2018.
- [25] R. Soloperto, M. A. Müller, S. Trimpe, and F. Allgöwer, “Learning-based robust model predictive control with state-dependent uncertainty,” *IFAC-PapersOnLine*, vol. 51, no. 20, pp. 442–447, 2018.
- [26] F. Berkenkamp, A. P. Schoellig, and A. Krause, “Safe controller optimization for quadrotors with gaussian processes,” in *2016 IEEE international conference on robotics and automation (ICRA)*, pp. 491–496, IEEE, 2016.
- [27] A. Marco, P. Hennig, J. Bohg, S. Schaal, and S. Trimpe, “Automatic lqr tuning based on gaussian process global optimization,” in *2016 IEEE international conference on robotics and automation (ICRA)*, pp. 270–277, IEEE, 2016.
- [28] F. D. Brunner, M. Lazar, and F. Allgöwer, “Stabilizing model predictive control: On the enlargement of the terminal set,” *International Journal of Robust and Nonlinear Control*, vol. 25, no. 15, pp. 2646–2670, 2015.
- [29] U. Rosolia and F. Borrelli, “Learning how to autonomously race a car: a predictive control approach,” *IEEE Transactions on Control Systems Technology*, vol. 28, no. 6, pp. 2713–2719, 2019.
- [30] P. Englert, N. A. Vien, and M. Toussaint, “Inverse kkt: Learning cost functions of manipulation tasks from demonstrations,” *The International Journal of Robotics Research*, vol. 36, no. 13-14, pp. 1474–1488, 2017.
- [31] T. Koller, F. Berkenkamp, M. Turchetta, and A. Krause, “Learning-based model predictive control for safe exploration,” in *2018 IEEE conference on decision and control (CDC)*, pp. 6059–6066, IEEE, 2018.
- [32] K. P. Wabersich, L. Hewing, A. Carron, and M. N. Zeilinger, “Probabilistic model predictive safety certification for learning-based control,” *IEEE Transactions on Automatic Control*, vol. 67, no. 1, pp. 176–188, 2021.
- [33] J. H. Gillulay and C. J. Tomlin, “Guaranteed safe online learning of a bounded system,” in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2979–2984, IEEE, 2011.
- [34] K. P. Wabersich and M. N. Zeilinger, “Safe exploration of nonlinear dynamical systems: A predictive safety filter for reinforcement learning,” *arXiv preprint arXiv:1812.05506*, 2018.
- [35] F. Berkenkamp, M. Turchetta, A. Schoellig, and A. Krause, “Safe model-based reinforcement learning with stability guarantees,” *Advances in neural information processing systems*, vol. 30, 2017.
- [36] F. Jenelten, J. He, F. Farshidian, and M. Hutter, “Dtc: Deep tracking control,” *Science Robotics*, vol. 9, Jan. 2024.
- [37] V. Tsounis, M. Alge, J. Lee, F. Farshidian, and M. Hutter, “Deepgait: Planning and control of quadrupedal gaits using deep reinforcement learning,” *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 3699–3706, 2020.
- [38] S. Gangapurwala, M. Geisert, R. Orsolino, M. Fallon, and I. Havoutis, “Real-time trajectory adaptation for quadrupedal locomotion using deep reinforcement learning,” in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5973–5979, IEEE, 2021.
- [39] L. Hewing, K. P. Wabersich, M. Menner, and M. N. Zeilinger, “Learning-based model predictive control: Toward safe learning in control,” *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 3, pp. 269–296, 2020.
- [40] NVIDIA, “NVIDIA Isaac Sim.” <https://developer.nvidia.com/isaac-sim>.
- [41] Google-DeepMind, “Mujoco 3.” <https://github.com/google-deepmind/mujoco/discussions/1101>.
- [42] N. Rudin, D. Hoeller, P. Reist, and M. Hutter, “Learning to walk in minutes using massively parallel deep reinforcement learning,” in *Conference on Robot Learning*, pp. 91–100, PMLR, 2022.
- [43] N. Rudin, D. Hoeller, M. Bjelonic, and M. Hutter, “Advanced skills by learning locomotion and local navigation end-to-end,” in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 2497–2503, IEEE, 2022.
- [44] F. Ruscelli, A. Laurenzi, N. G. Tsagarakis, and E. M. Hoffman, “Horizon: a trajectory optimization framework for robotic systems,” *Frontiers in Robotics and AI*, vol. 9, 2022.
- [45] A. Patrizi, “SharsorIPCCpp.” <https://github.com/AndrePatri/SharsorIPCCpp>, 2023.
- [46] A. Patrizi, “OmniRoboGym.” <https://github.com/AndrePatri/OmniRoboGym>, 2023.
- [47] A. Patrizi, “CoClusterBridge.” <https://github.com/AndrePatri/CoClusterBridge>, 2023.
- [48] A. Patrizi, “RHCviz.” <https://github.com/AndrePatri/RHCviz>, 2023.
- [49] A. Patrizi, “LRHControl.” <https://github.com/AndrePatri/LRHControl>, 2023.