Real World Deployment of Model-based Quadruped Locomotion Controller Using Model-Free Safe Bayesian Optimization

Motivation: State-of-the-art model-based control methods are capable of performing highly agile and dynamic legged locomotion [1, 2]. However, they require an accurate system dynamics model that is often unavailable due to our limited understanding of real-world physics and inevitable simplifications for reducing computational burden. Therefore, model-based controllers often do not perform well off-the-shelf on hardware and require considerable parameter tuning. This tuning process is time-consuming and in some instances can also harm the hardware. Furthermore, it may have to be repeated for different environment settings or, in case of legged robots, gait patterns.

Goal: We pursue to improve the robustness and the tracking performance of a model-based controller on robot hardware by bridging the gap between simplified/modelled and real-world dynamics.

Approach: Bayesian optimization [3] is a sample-efficient method often used to learn optimal control parameters from data recorded directly on hardware in a model-free fashion [4, 5]. In particular, it can be combined with safety-related constraints to learn the control parameters while providing high-probability safety guarantees for the hardware [6, 7, 8, 9]. The student will leverage existing safe model-free learning methods [6, 7, 8, 9] to learn optimal feedback control parameters of each joint that are applied to compensate model mismatches. This set of parameters can allow a robot to track control signals computed by a whole-body controller [10] with a better performance. Furthermore, the student will investigate the sensitivity of these parameters towards different gait patters, which would be included into the Bayesian optimization framework as contexts [11]. On course of the project, the student will evaluate the approach on a simulation of the robot by deliberately introducing model-imprecisions. Then, hardware experiments will be performed by the student to solve the task for the real system with a commercial legged robotic platform *Unitree A1* [12].

General Details: The thesis is co-supervised by Prof. Andreas Krause and Prof. Stelian Coros. The student will have the opportunity to study and understand state-of-the-art model-based control methods for legged locomotion as well as model-free reinforcement learning algorithms that come with strong theoretical guarantees and also apply these methods to a real-world system.

Interested? Reach out to Bhavya Sukhija (sukhijab@ethz.ch) and Dongho Kang (kangd@ethz.ch) with your CV and transcript of grades.

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References

[1] D. Kim, J. Di Carlo, B. Katz, G. Bledt, and S. Kim, "Highly dynamic quadruped locomotion via whole-body impulse control and model predictive control," *arXiv preprint arXiv:1909.06586*, 2019.

[2] G. Bledt and S. Kim, "Implementing regularized predictive control for simultaneous real-time footstep and ground reaction force optimization," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 6316–6323, IEEE, 2019.

[3] J. Mockus, V. Tiesis, and A. Zilinskas, "The application of Bayesian methods for seeking the extremum," *Towards Global Optimization*, vol. 2, no. 117-129, p. 2, 1978.

[4] R. Calandra, A. Seyfarth, J. Peters, and M. Deisenroth, "Bayesian optimization for learning gaits under uncertainty," *Annals of Mathematics and Artificial Intelligence*, vol. 76, pp. 5–23, 2016.

[5] A. Marco, P. Hennig, J. Bohg, S. Schaal, and S. Trimpe, "Automatic LQR tuning based on Gaussian process global optimization," in *IEEE International Conference on Robotics and Automation*, pp. 270–277, 2016.

[6] Y. Sui, A. Gotovos, J. Burdick, and A. Krause, "Safe exploration for optimization with Gaussian processes," in *International Conference on Machine Learning*, pp. 997–1005, 2015.

[7] F. Berkenkamp, A. Krause, and A. P. Schoellig, "Bayesian optimization with safety constraints: safe and automatic parameter tuning in robotics," *Machine Learning*, 2021.

[8] D. Baumann, A. Marco, M. Turchetta, and S. Trimpe, "GoSafe: Globally optimal safe robot learning," in *IEEE International Conference on Robotics and Automation*, pp. 4452–4458, 2021. Proofs in extended online version: arXiv 2105.13281.

[9] B. Sukhija, M. Turchetta, D. Lindner, A. Krause, S. Trimpe, and D. Baumann, "Scalable safe exploration for global optimization of dynamical systems," *arXiv preprent arXiv:2201.09562*, 2022.

[10] D. Kang, S. Zimmermann, and S. Coros, "Animal gaits on quadrupedal robots using motion matching and model-based control," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 8500–8507, IEEE.

[11] A. Krause and C. Ong, "Contextual Gaussian process bandit optimization," in *Advances in Neural Information Processing Systems*, pp. 2447–2455, 2011.

[12] Unitree Robotics. `https://www.unitree.com/products/a1`.