Locomotion Adaption over Soft Terrain

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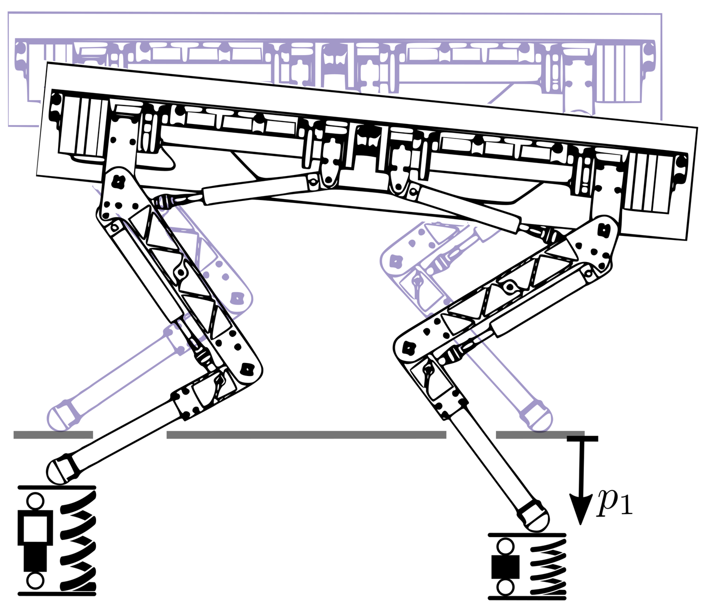
Introduction

Over soft terrain, the ground introduces unmodelled contact dynamics that the controller is not accounting for. This affects the stability and performance of the robot. We present an approach for locomotion adaptation over soft terrain in which we re-formulate the whole-body optimization (WBOpt) problem by including the contact dynamics and learning the terrain parameters online.



Whole-body Control

- Execute tasks (balancing, locomotion, tracking, etc.) subject to constraints
- Reformulate the control problem as a WBOpt problem using QP [1]
- Robot Dynamics:

$$M(q)\ddot{q} + h(q,\dot{q}) = S^T\tau + J_s(q)^T\lambda \tag{1}$$

Contact Model:

$$\lambda_i = \{[\lambda_{i,\perp}^T \lambda_{i,\parallel}^T]^T : \lambda_{i,\perp} = -\kappa p_i - \delta \dot{x}_i, \lambda_{i,\parallel} = \mu \lambda_{i,\perp}\} \quad \forall p_i \leq 0 \tag{2}$$

WBOpt:

$$\underset{\mathbf{u}\,=\,\{\ddot{q},\lambda,\epsilon\}}{\text{minimize}} \quad \|\mathrm{G}\mathbf{u} - \Upsilon_{\mathrm{des}}\|_{\mathrm{s}}^2 + \|\mathbf{u}\|_{\mathbf{W}}^2 + \|\epsilon\|_{\rho}^2 \tag{3}$$

s.t. Dynamic Consistency: $M_f\ddot{q} + h_f = J_{s_f}^T\lambda$

Torque Limits: $\tau_{min} \leq S_a^{-T}(M_a\ddot{q} + h_a - J_{s_a}^T\lambda) \leq \tau_{max}$

Joint Limits: $\ddot{q}_{j\,min} \leq \ddot{q}_j \leq \ddot{q}_{j\,max}$

Friction Cone: $\underline{\mathrm{d}}_{fr} < \lambda_{i,\parallel} < \bar{\mathrm{d}}_{fr}$

Swing Feet Task: $\ddot{x}_{f_{sw}}(q) = J_{sw}\ddot{q} + \dot{J}_{sw}\dot{q} = \ddot{x}_{f_{sw}}^r$

Stance Feet Condition: $\ddot{x}_{f_{st}}(q) = J_{st}\ddot{q} + \dot{J}_{st}\dot{q} = M_f^{-1}(-\kappa\epsilon - \delta\dot{x}_{f_{st}})$ (4)

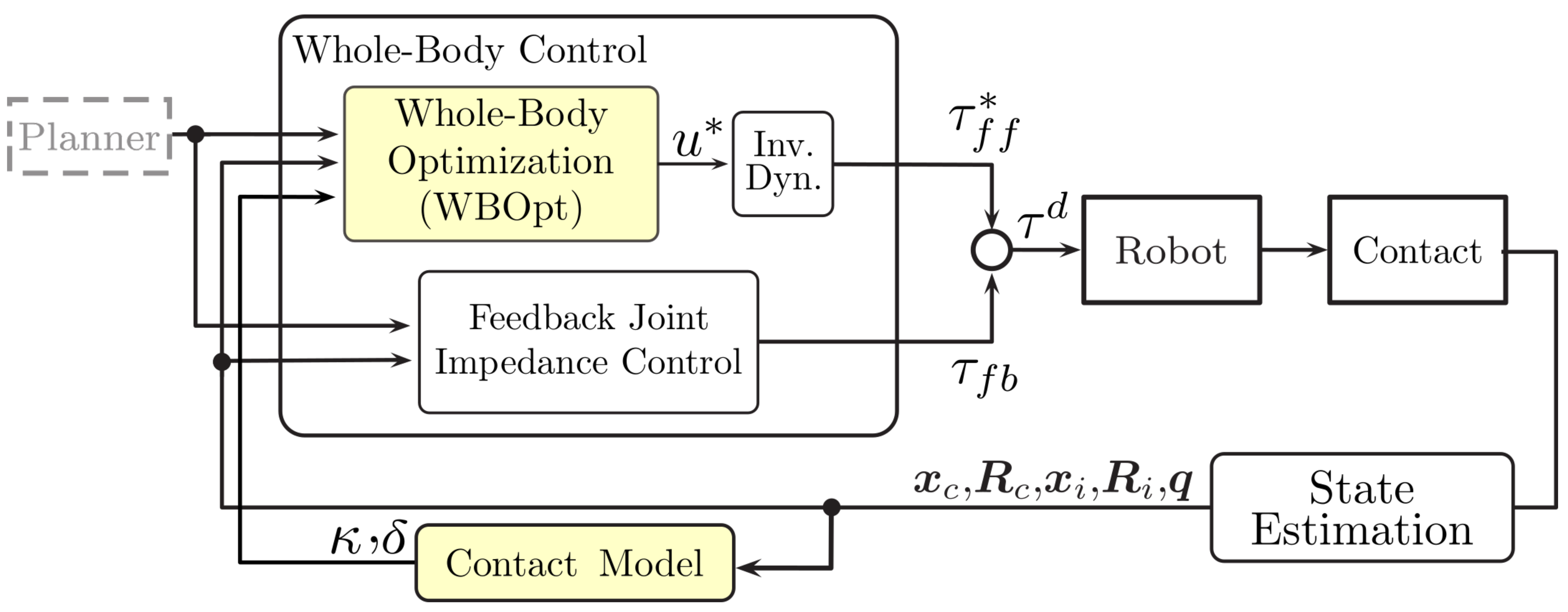
Softening: $\epsilon \geq 0$ (5)

- $\mathbf{u} = [\ddot{\mathbf{q}}^T, \boldsymbol{\lambda}^T]^T \in \mathbb{R}^{6+n+3c}$ ➞ generalized accelerations and contact forces
- Map the optimal policy $\mathbf{u}^*$ into desired feed-forward joint torques $\boldsymbol{\tau}_{ff}^* \in \mathbb{R}^n$:

$$\boldsymbol{\tau}_{ff}^* = \begin{bmatrix}\mathbf{M}_{bj}^T & \mathbf{M}_j\end{bmatrix}\ddot{\mathbf{q}}^* + \mathbf{h}_j - \mathbf{J}_{cj}^T\boldsymbol{\lambda}^* \tag{6}$$

- Sum them up with the joint PD feedback torques $\boldsymbol{\tau}_{fb}$ into desired torques:

$$\boldsymbol{\tau}^d = \boldsymbol{\tau}_{ff}^* + PD(\mathbf{q}_j^d, \dot{\mathbf{q}}_j^d), \tag{7}$$

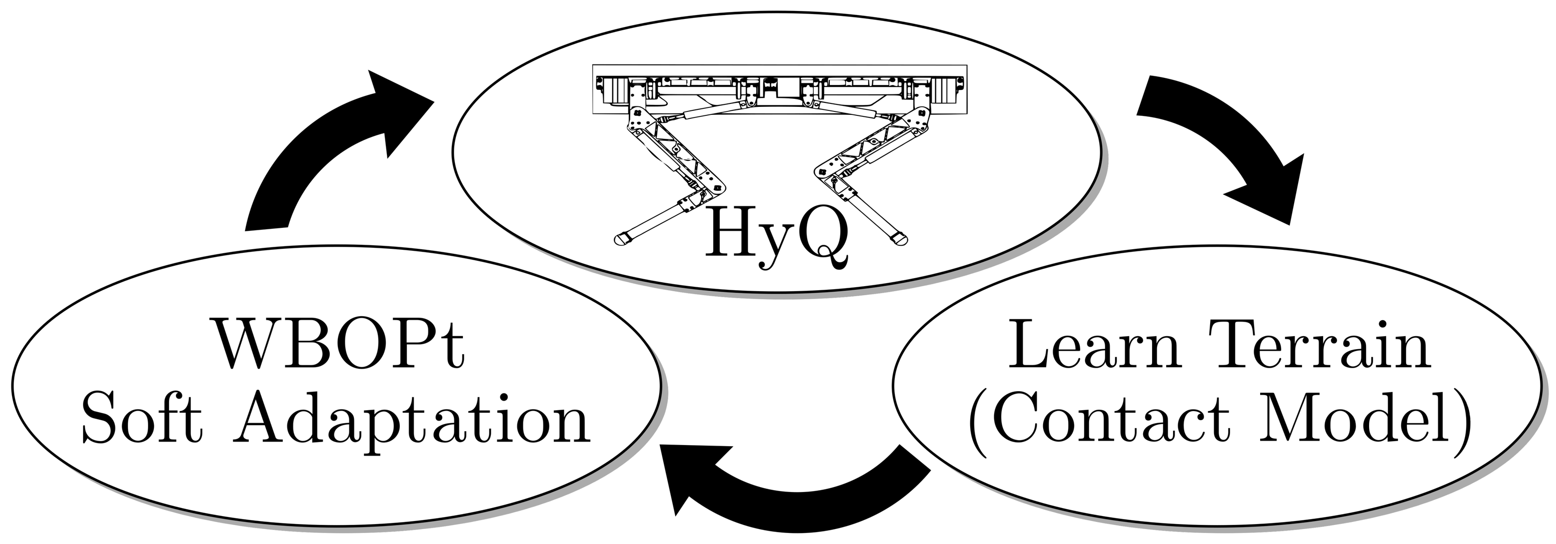


Contact Model

- Problems of Soft Terrain:
  - Robot's feet exhibit compliant behavior while in contact with the ground
  - The unmodelled contact dynamics must be incorporated in the WBOpt
  - Multiple models describe the dynamics of the ground interaction [2]
- Viscoelastic model (2):
  - κ and δ ➞ equivalent ground impedance (i.e., stiffness and damping)
  - $p_i = x_{i0} - x_i$ ➞ ground penetration of the i^{th} foot
- The contact forces could be then computed as a function of the ground impedance (κ and δ) and the feet states $\lambda = f(\kappa, \delta, \mu, x_{i0}, x_i)$
- Yet, in unstructured environments, the ground impedance are unknown

Soft Terrain Estimation

- Overview
  - ✓ Terrain knowledge is incorporated in the WBOpt ➞ contact model
  - Contact model parameters (ground impedance) are learned on-line
- Parametric regression:
  - Using (2), estimate the ground impedance based on the robot's states
  - Directly used for task space impedance control
  - Numerically stable, computationally efficient but low dimensional
- Non-parametric regression
  - Coutinho et al. [3] Neural Network was used to estimate the terrain stiffness based on the robot states during manipulation
  - Chang et al. [4]: Gaussian Process based Regression (GPR) was used to learn the terrain parameters on-line for a one leg jumping robot
  - Grandia et al. [5]: Locally Weighted Projection Regression and Sparse GPR to learn the unmodeled rigid body dynamic errors in legged robots
- Reinforcement Learning (RL):
  - RL based variable impedance control: re-tune the controller gains on-line based on the ground impedance
  - In manipulation Policy Improvement with Path Integrals (PI^2) sampling was utilized to tune the impedance controller gains [6]
  - Also in quadruped locomotion [7], the gait parameters and impedance controller gains of the robot were optimized to improve its performance



Summary

- Locomotion adaptation over soft terrain:
  - ① WBOpt: models the contact dynamics and adapts its QP formulation
  - ② Terrain estimator: learns the terrain parameters online
- Advantages:
  - The discontinuity due to the linear complementarity constraints at the contact interaction [8] is avoided.
  - The numerical solution of the OP is stable and computationally efficient
  - Various types of terrain (including stiff terrain) could be generalized [9]

References

[1] C. Mastalli, et al. "Motion planning for challenging locomotion: a study of decoupled and coupled approaches.", preprint, 2018.

[2] L. Ding, et al. "Foot–terrain interaction mechanics for legged robots: Modeling and experimental validation," (IJRR), 2013.

[3] F. Coutinho, et al. "A neural-based approach for stiffness estimation in robotic tasks", *International Conference on Advanced Robotics (ICAR)*, 2013.

[4] A. H. Chang, et al. "Learning to jump in granular media: Unifying optimal control synthesis with gaussian process-based regression," *(ICRA)*, 2017.

[5] R. Grandia, et al. "Contact invariant model learning for legged robot locomotion", *IEEE Robotics and Automation Letters*, 2018.

[6] J. Buchli, et al. "Variable Impedance Control A Reinforcement Learning Approach", *Robotics: Science and Systems Conference (RSS)*, 2010.

[7] E. Heijmink, et al. "Learning optimal gait parameters and impedance profiles for legged locomotion", *Humanoids*, 2017.

[8] M. Neunert, et al. "Whole-Body Nonlinear Model Predictive Control Through Contacts for Quadrupeds", preprint, 2017.

[9] M. Azad et al. "A new nonlinear model of contact normal force", *IEEE Transactions on Robotics*, 2014.