STANCE: Locomotion Adaptation over Soft Terrain

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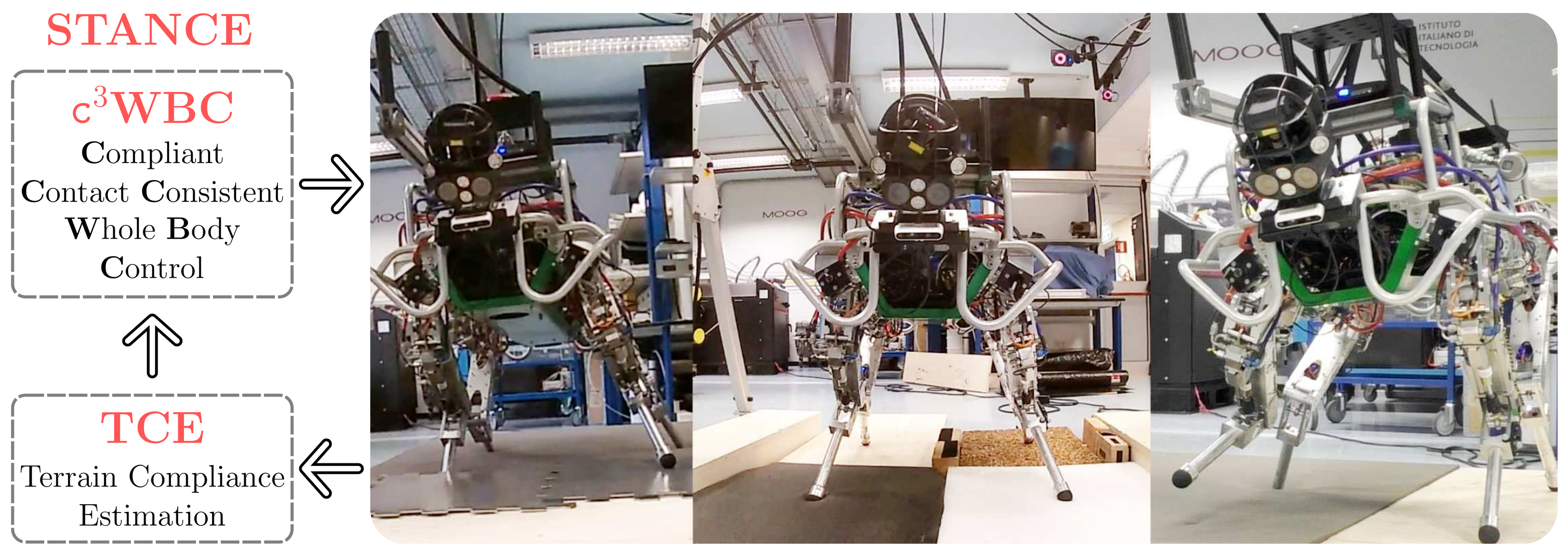
Let's talk here!

STANCE in a nutshell



Why is locomotion over soft terrain hard?

Whole-Body Control (WBC) frameworks are not **terrain aware**; they assume that the robot is walking over rigid terrain. When the terrain is not rigid, the **unmodeled** contact dynamics is not accounted for in the control strategy. This introduces **uncertainty** in locomotion that affects the robot's stability and performance.

How to solve this?

We can extend the WBC formulation with a more generic contact model that can handle rigid and soft terrain dynamics. By that, we can adapt to any type of terrain by estimating the its impedance parameters online, and feeding it back to the WBC.

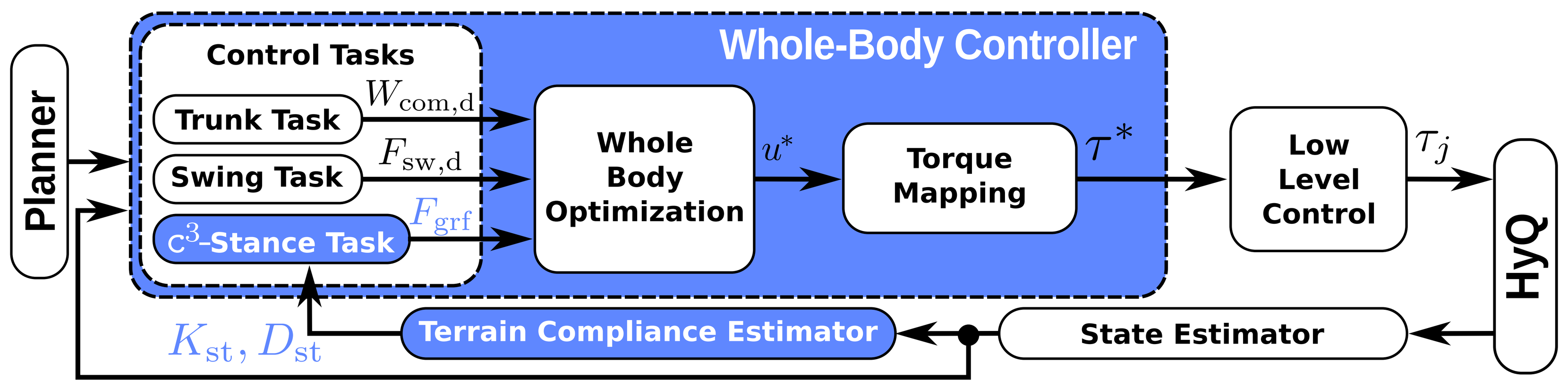
What is our approach?

Soft **T**errain **A**daptation a**N**d **C**ompliance **E**stimation (STANCE) is a soft terrain adaptation algorithm that allows HyQ to adapt its locomotion strategy **online** to any type of terrain compliance (stiff or soft) **without** pre-tuning. STANCE consists of **Compliant Contact Consistent Whole-Body Control (c^{3}WBC)** and a **Terrain Compliance Estimator (TCE)**. The c^{3}WBC adapts to any type of compliant terrain *given the terrain parameters* that are estimated *online* via the TCE.

Why is this cool?

Unlike previous work on WBC, we do not assume that the ground is rigid. With STANCE, HyQ can traverse and transition between multiple terrains with different compliance **without** pre-tuning. Each leg independently senses and adapts to changes in terrain compliance. Thus, the robot is always **compliant contact consistent** (c^3) with the terrain which makes STANCE more robust in challenging scenarios compared to the baseline approaches.

Whole-Body Control (WBC)



Objective:

- Track the planned trajectories (control tasks) & keep the robot balanced
- Respect the robot dynamics and actuation & kinematic limits
- Respect the contact dynamics (remain c^3) and friction constraints
- The c^{3}WBC is c^3 while the standard WBC is rigid contact consistent

How is it done?

- Recall the robot dynamics:

$$M_u(q)\ddot{q} + h_u(q,\dot{q}) = J_{\text{st},u}(q)^T F_{\text{grf}} \quad (1)$$

$$M_a(q)\ddot{q} + h_j(q,\dot{q}) = \tau_j + J_{\text{st},j}(q)^T F_{\text{grf}} \quad (2)$$

- Formulate a Whole-Body Optimization (WBOpt) problem via QP
- Solve for the optimal generalized acceleration $\ddot{q}^*$ and contact forces F^*_{grf}
- Map the optimal solution into desired joint torques:

$$\tau^* = M_a\ddot{q}^* + h_j - J^T_{\text{st},j}F^*_{\text{grf}} \quad (3)$$

Whole Body Optimization (WBOpt)

(Trunk Task) $$\min_u \|W_{\text{com}} - W_{\text{com,d}}\|^2_Q + \|u\|^2_R \quad (4)$$

(Decision Variables) $$u = [\ddot{q}^T \; F^T_{\text{grf}} \; \eta^T \; \epsilon^T]^T$$

s.t.:

(Physical Consistency) $$M_u\ddot{q} + h_u = J^T_{\text{st},u}F_{\text{grf}} \quad (5)$$

~~(Stance Task)~~ $$\cancel{\dot{v}_{\text{st}} = J_{\text{st}}\ddot{q} + \dot{J}_{\text{st}}\dot{q} = 0} \quad (6)$$

(c^3-Stance Task) $$F_{\text{grf}} = K_{\text{st}}\epsilon + D_{\text{st}}\dot{\epsilon} \quad (7)$$

$$\dot{v}_{\text{st}} = J_{\text{st}}\ddot{q} + \dot{J}_{\text{st}}\dot{q} = -\ddot{\epsilon} \quad (8)$$

$$\epsilon \geq 0 \quad (9)$$

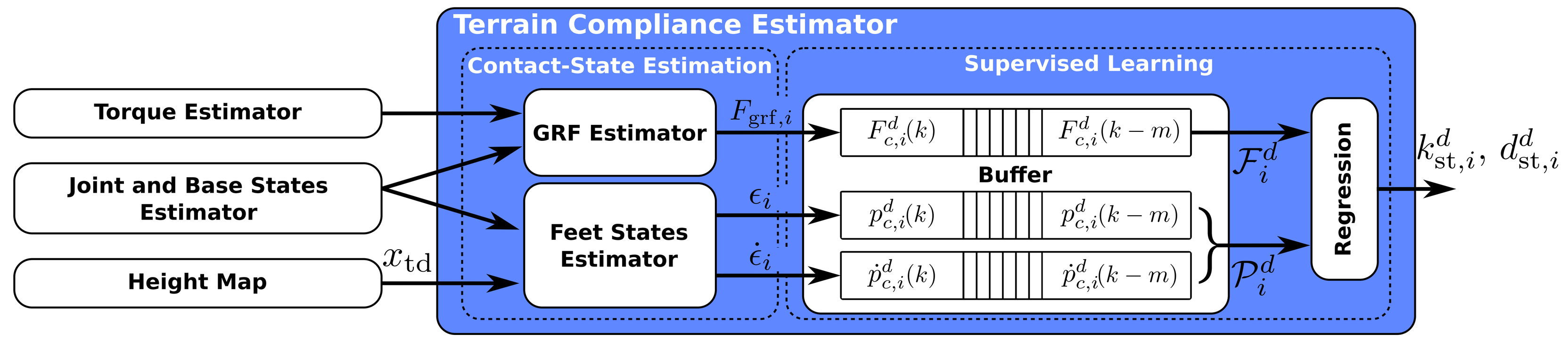
(Friction) $$|F_{\text{grf},\parallel}| \leq \mu |F_{\text{grf},\perp}| \quad (10)$$

(Normal Contact Force) $$F_{\min} \leq F_{\text{grf},\perp} \leq F_{\max} \quad (11)$$

(Swing Task) $$-\eta \leq \dot{v}_{\text{sw}} - \dot{v}_{\text{sw,d}} \leq \eta, \; \eta \geq 0 \quad (12)$$

(Torque and Joint Limits) $$\tau_{\min} \leq \tau_j \leq \tau_{\max}, \; \ddot{q}_{j_{\min}} \leq \ddot{q}_j \leq \ddot{q}_{j_{\max}} \quad (13)$$

Terrain Compliance Estimation (TCE)

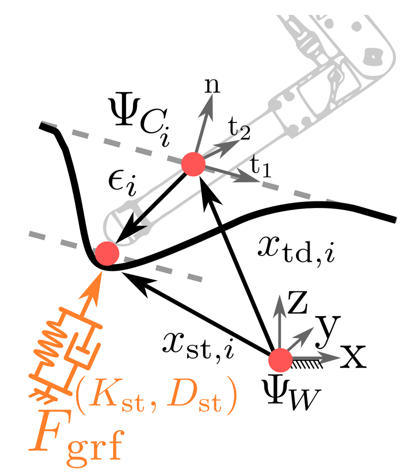


Objective:

The TCE estimates online the terrain compliance parameters (K_{st} and D_{st}) based on the states of the robot, and feeds them back to the c^{3}WBC.

How is it done?

We consider the contact model (7), and estimate its actual states (F_{grf}, ϵ, and $\dot{\epsilon}$). At every time instant, we collect the contact states of the previous m time instances, and using online regression, we solve for the terrain parameters.



Limitations of STANCE

State Estimation over Soft Terrain:

Our state estimator relies on leg odometry which assumes that the ground is rigid. Thus, the state estimator has difficulty determining when a foot is in contact with the ground over soft terrain (i.e., is the foot in the air, or compressing the surface?). This causes the leg odometry signal to drift jeopardizing the estimation. Our WBC is robust against a drifting state estimator, but the TCE is not; it still requires an accurate and non drifting estimate of the feet position in the world frame.

Low level control:

Over soft terrain, the dynamics of the environment also plays a role and must be considered in analyzing the stability of the system including the low level control. We experienced this during experiment where we noticed instabilities in the low level torque control loop. This is because interacting with soft terrain reduces the stability margins of the closed loop system. So you can't use high torque gains (like the ones we used previously for rigid terrain).

Minor Differences in Less Dynamic Motions:

STANCE was able to outperform the standard WBC during aggressive and dynamic motion. However, for a slow (less dynamic) motion, the outperformance of STANCE compared to the standard WBC was minor.

For more info.

Everything you need: `shamelfahmi.com/research/icra`

Related publication:

S. Fahmi, et. al., "STANCE: Locomotion Adaptation Over Soft Terrain," in IEEE Trans. Robot. (T-RO), April 2020.