A Comprehensive Framework for Legged Robots to Learn Diverse and Robust Gaits

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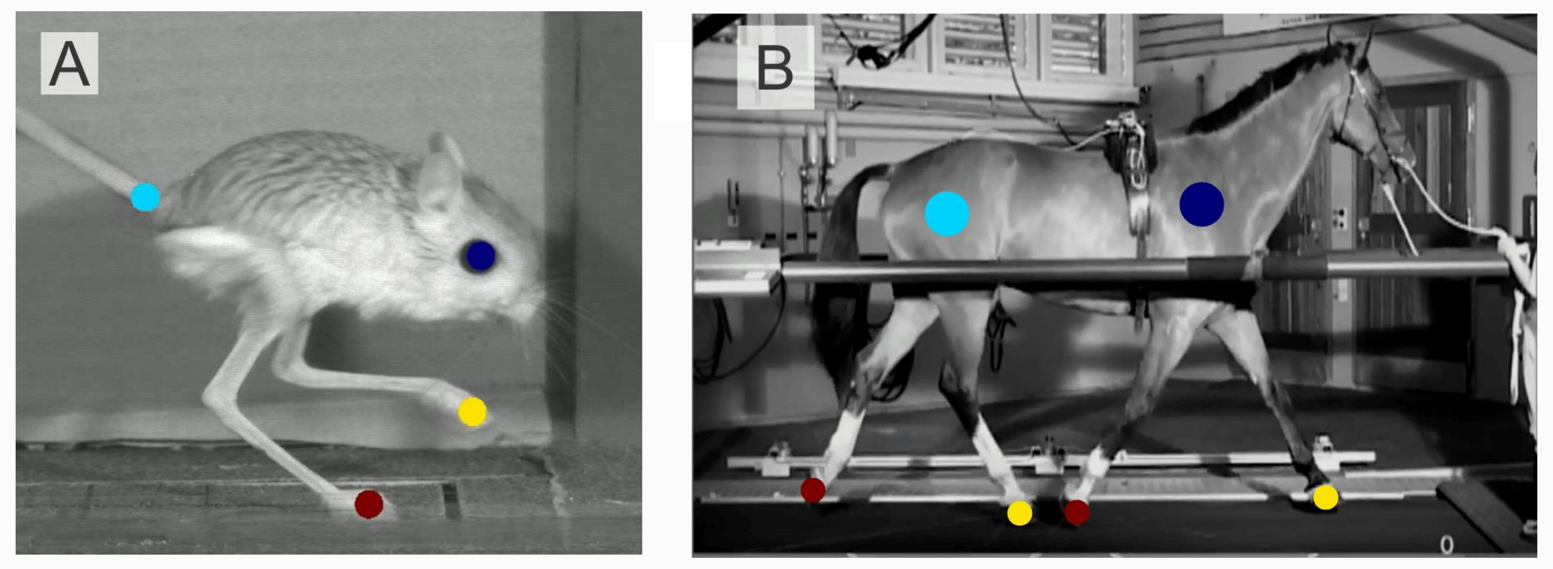
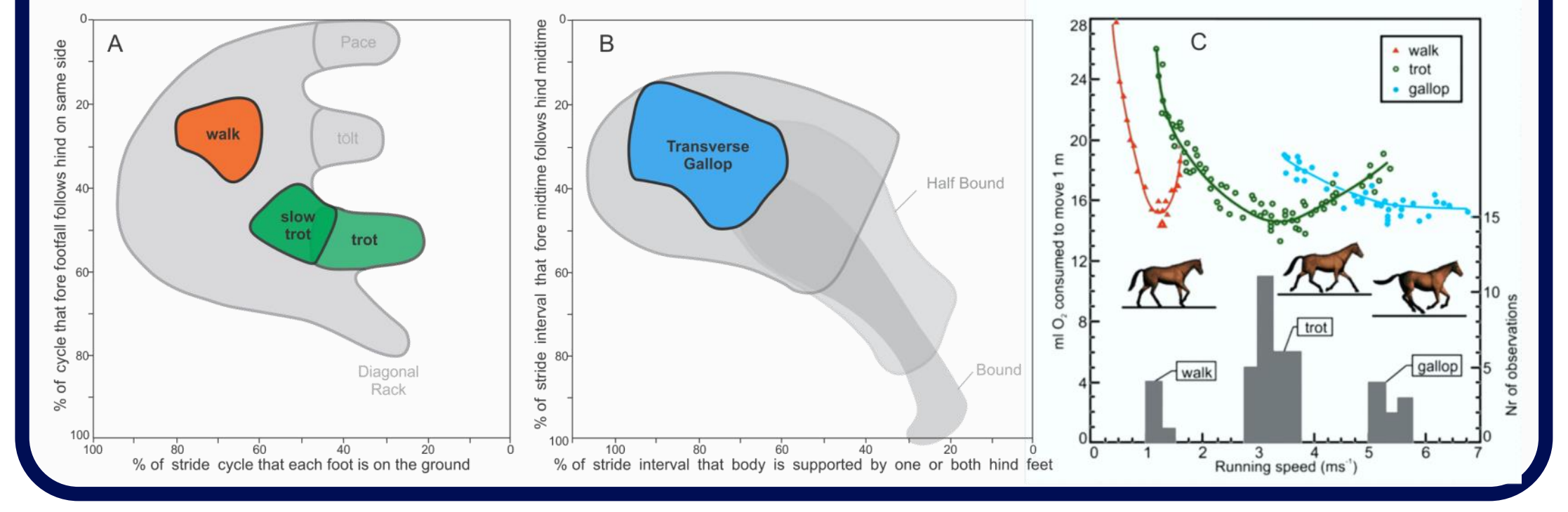
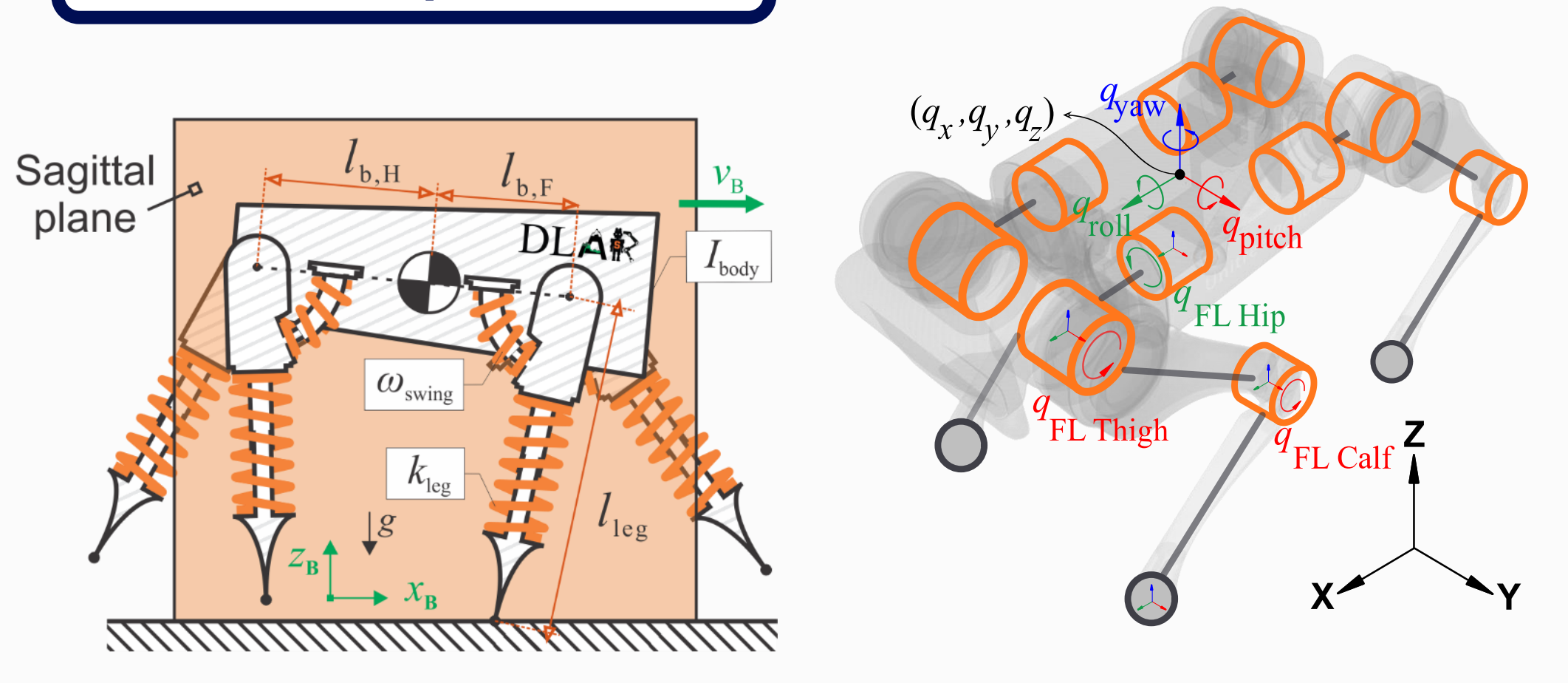
Motivation



Legged robots including bipedal humanoid robots and quadrupedal robots have substantial potential to relieve humans from tedious, repetitive, and dangerous tasks. Unfortunately, existing robots do not meet our expectations. We want to propose a framework that can let the robot explore different gait patterns such as walking, trotting and galloping [1, 2] to improve their performance in terms of their agility, efficiency, and stability.



Model Dynamics



Quadrupedal SLIP Model   A1 Model

- In different gaits, the robot passes through several phases in which different pairs of legs alternate between stance and flight. We have four phases in total:

  1) All Stance ($\mathcal{F}_A$)   2) Front Stance ($\mathcal{F}_F$)
  3) Rear Stance ($\mathcal{F}_R$)   4) Flight ($\mathcal{F}_T$)

- By combining the equation of motion and the corresponding holonomic constraints of each phase listed above, we obtain the following differential-algebraic equations for each domain:

$$\begin{bmatrix} M(q) & -J_*^T(q) \\ J_*(q) & 0 \end{bmatrix}\begin{bmatrix} \ddot{q} \\ \lambda_* \end{bmatrix} = \begin{bmatrix} S\tau - C(q,\dot{q}) - G(q) \\ -\dot{J}_*(q,\dot{q})\dot{q} \end{bmatrix}$$

Example: Hybrid model of the pronking gait,

$$\Sigma_{\mathrm{PF}} : \begin{cases} \mathcal{F}_A, (q,\dot{q}) \notin S_A^{\mathrm{LO}};\ \dot{q}^+ = \Delta_{\mathcal{F}_A \to \mathcal{F}_T}\dot{q}^-, (q,\dot{q}) \in S_A^{\mathrm{LO}}; \\ \mathcal{F}_T, (q,\dot{q}) \notin S_A^{\mathrm{TD}};\ \dot{q}^+ = \Delta_{\mathcal{F}_T \to \mathcal{F}_A}\dot{q}^-, (q,\dot{q}) \in S_A^{\mathrm{TD}}; \end{cases}$$

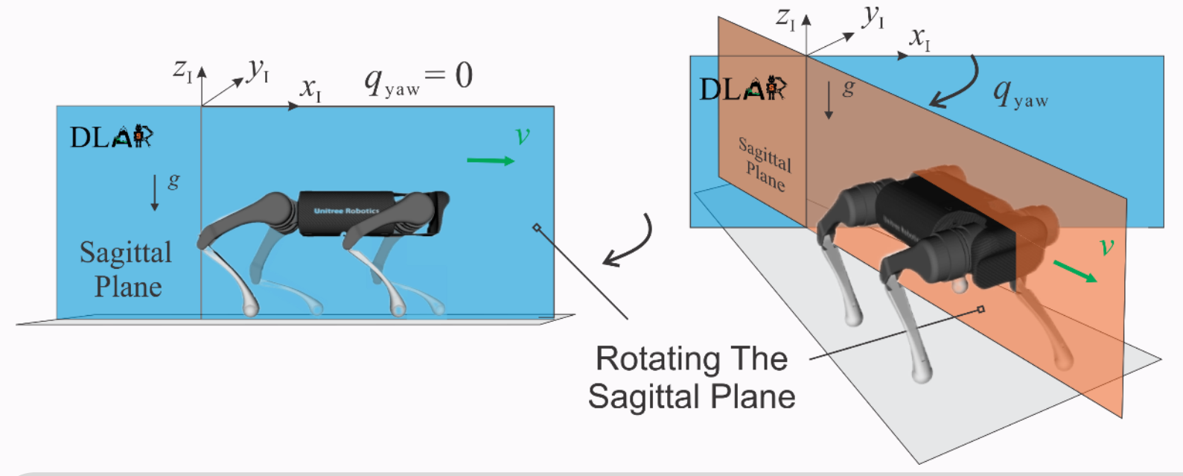
- The resulting NLP optimization problem were constructed and solved using the open-source framework FROST.

T1: Gait Structure

We aim to generalize the symmetries in legged locomotion using **group theory** [3] and demonstrate how breaking symmetries can lead to diverse gaits in a legged system. This study can provide insight into why animals of different morphologies prefer certain gaits and how they can transition between gaits at a given speed. Additionally, symmetries are important for the locomotion controller design in stabilizing the legged systems.

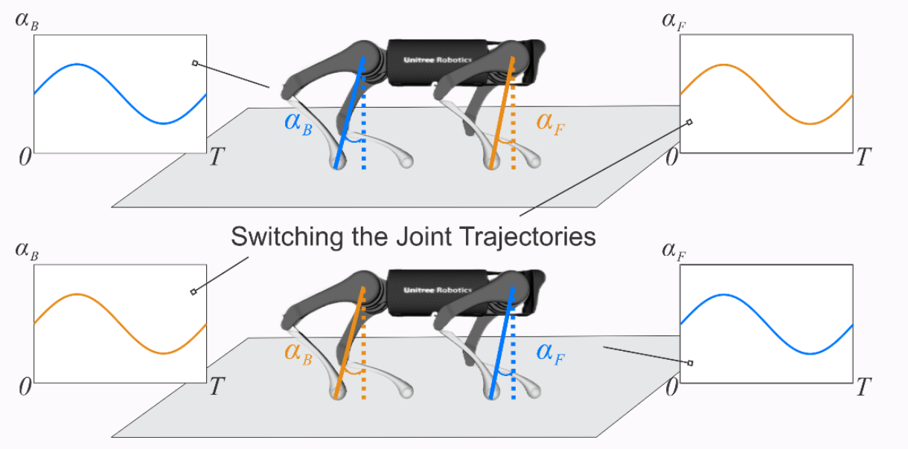
Torso rigid motion symmetry

- Rotating the sagittal plane with an angle q_{yaw} will result a periodic solution:



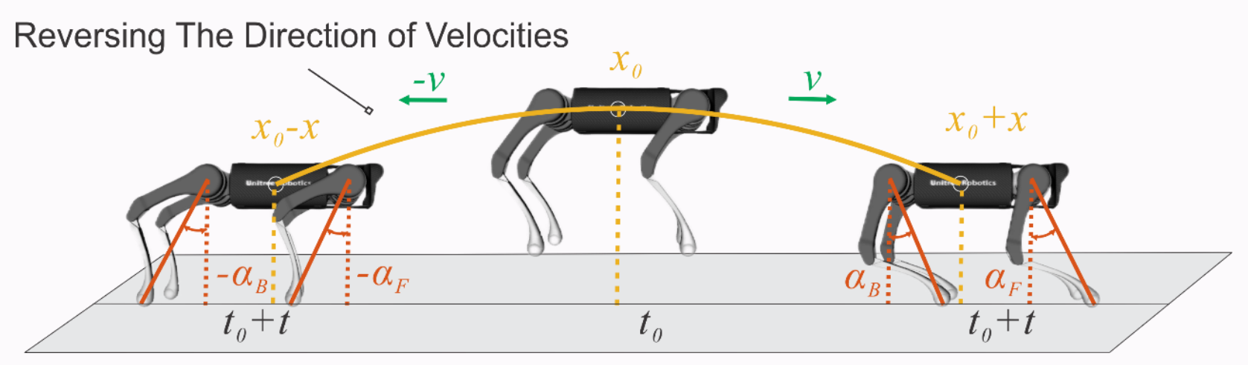
Leg permutation symmetry

- Switching the states of legs with certain phase lag will result a periodic solution:

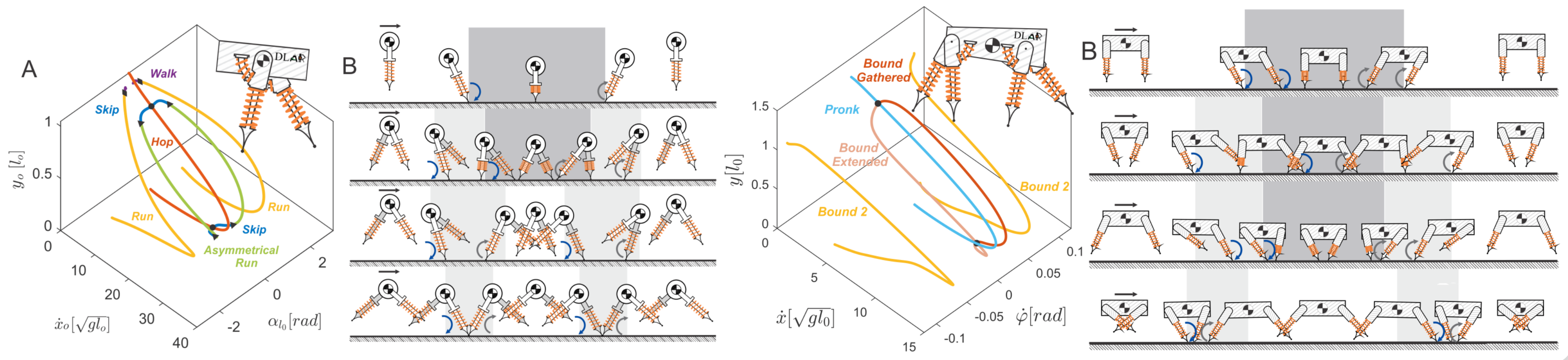


Time-reversal symmetry

- Reversing the speeds of the system will result a periodic solution:

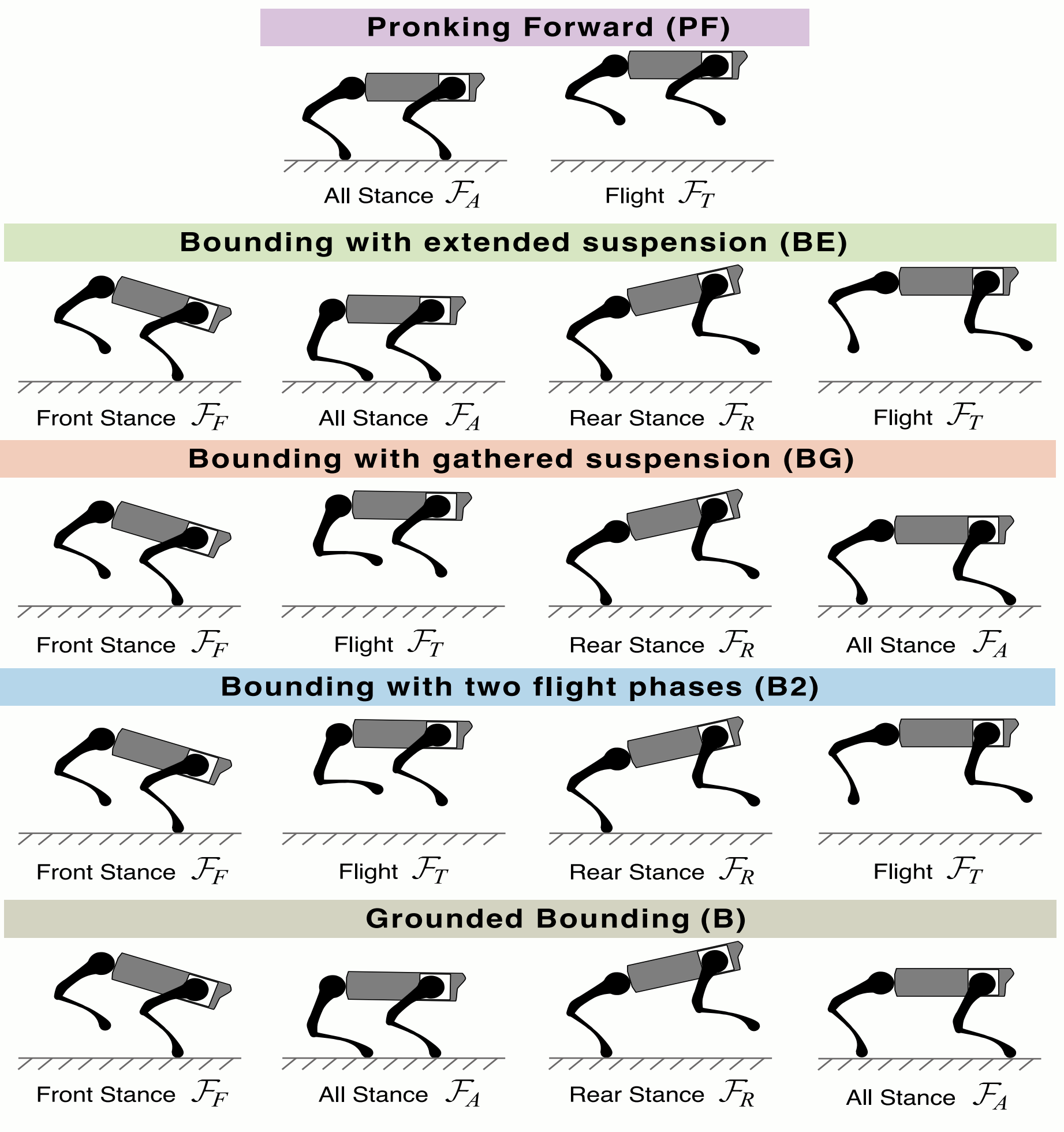


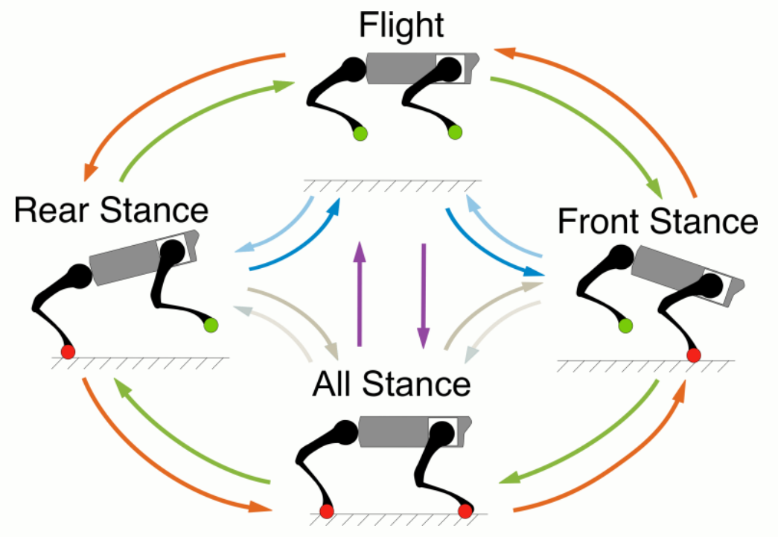
Most of the common bipedal and quadrupedal gaits of the proposed SLIP models with full symmetry can be found through **numerical continuations** [3], and diverse gait patterns are identified through bifurcations and breaking of symmetries in the torso and leg motions.

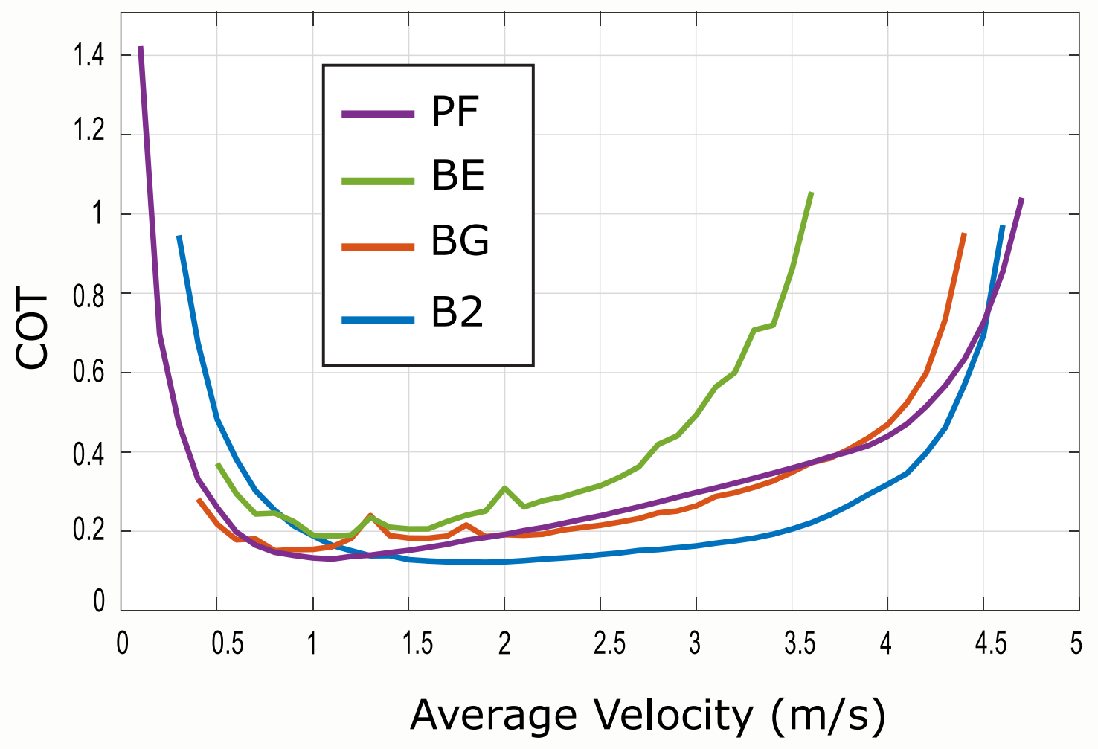


T2: Gait Governor

To understand how a specific footfall pattern will change the energetics of a legged system, we use full body models of robots with desired footfall sequences and rigid impacts. In order to find the most energy efficient gait, we used optimal control methods to formulate the problem as a **trajectory optimization (TO)** [4] problem with proper constraints and objective function. The transition is controlled by the **reference governor (RG)** this is guaranteed to be safe.







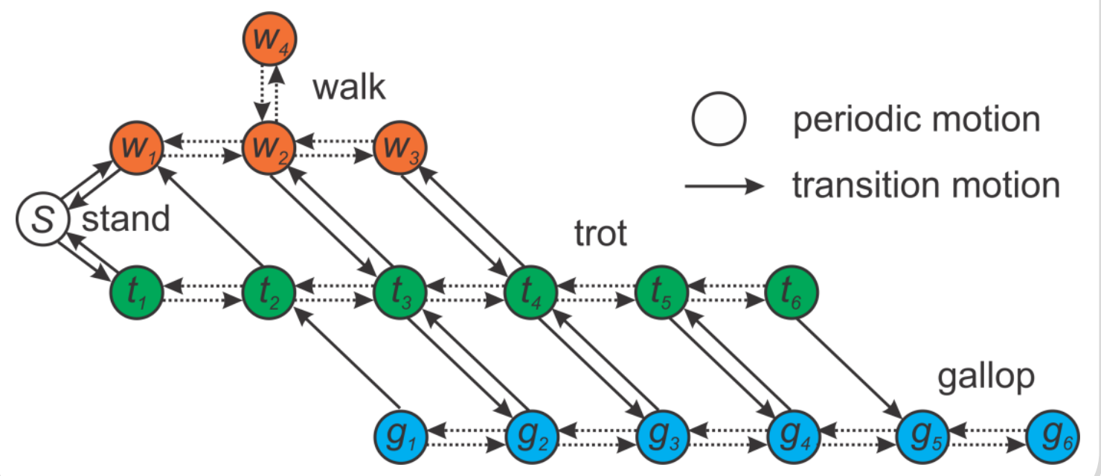
Finding an optimal gait of the robot is equivalent to finding states trajectories to one of the hybrid models while minimizing the cost of transport (COT).

Assume the nonlinear system model has the form with the constraints:

$$x(t+1) = f(x(t), v(t), w(t))$$
$$y(t) = h(x(t)) \le 0$$

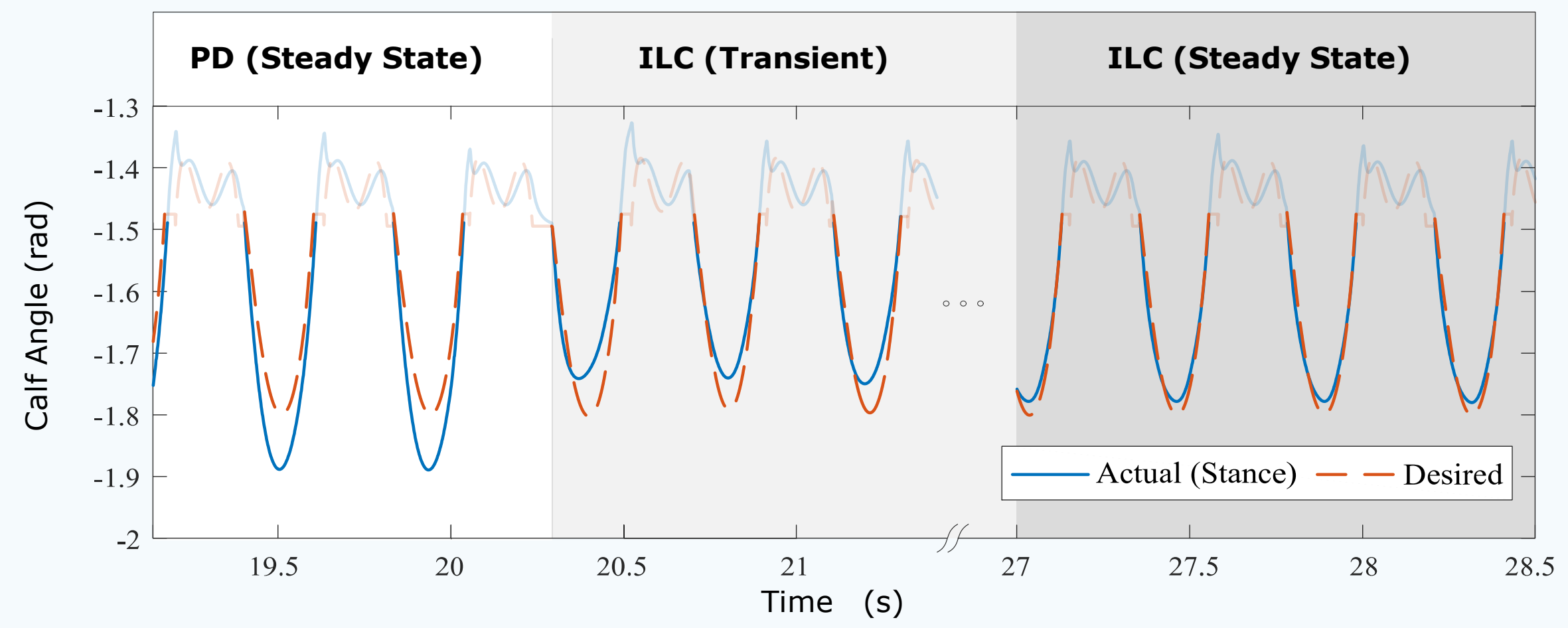
$$J = \| v(t) - r(t) \|_Q^2$$
$$= (v(t) - r(t))^T Q (v(t) - r(t))$$

- where Q is minimized with respect to $v(t)$ subject to the constraints $S(x, v)$.
- $v(t)$ is computed by solving a quadratic programming problem combined with **graph theory** either online or offline as a piecewise affine function of $x(t)$ and $r(t)$.

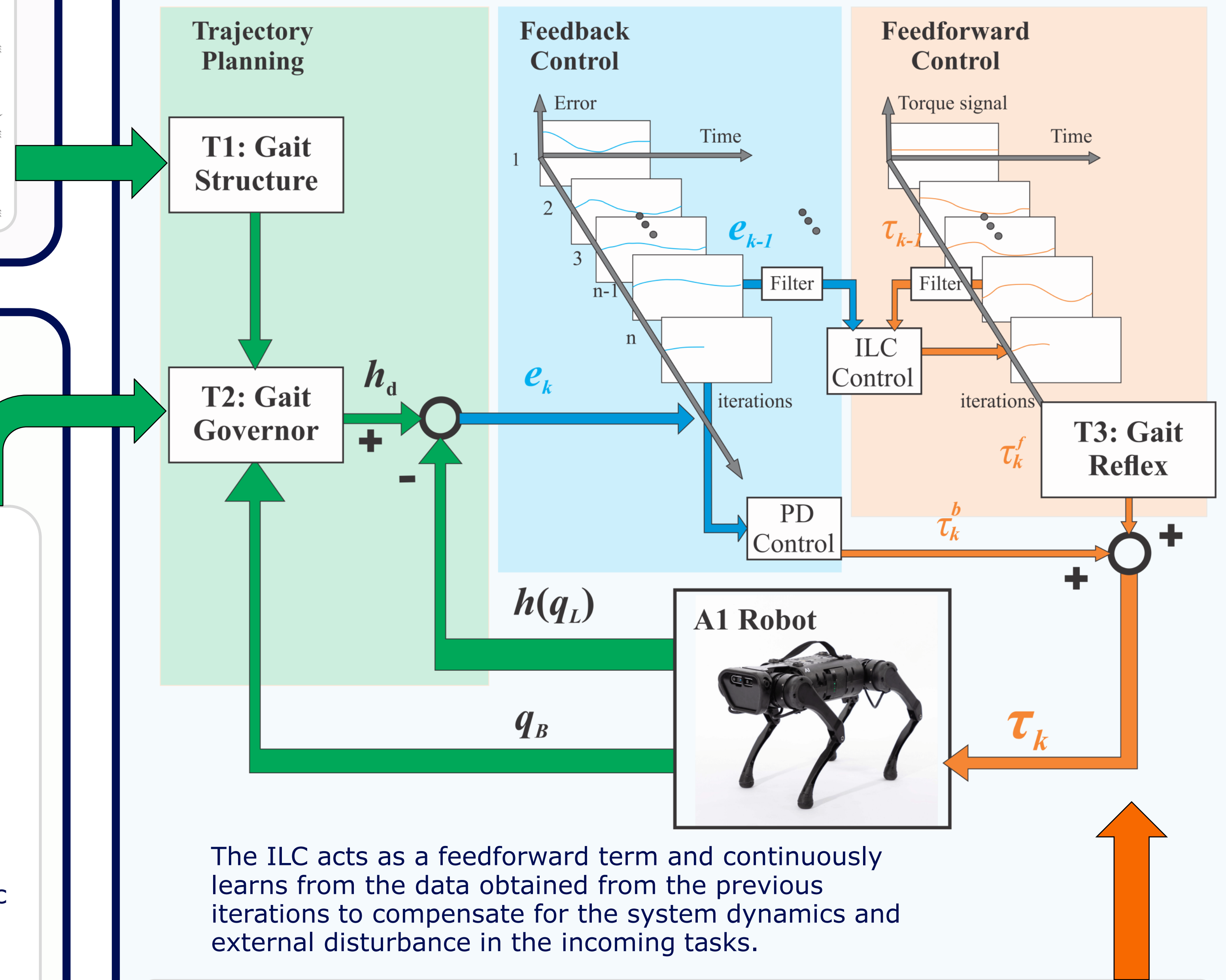


T3: Gait Reflex

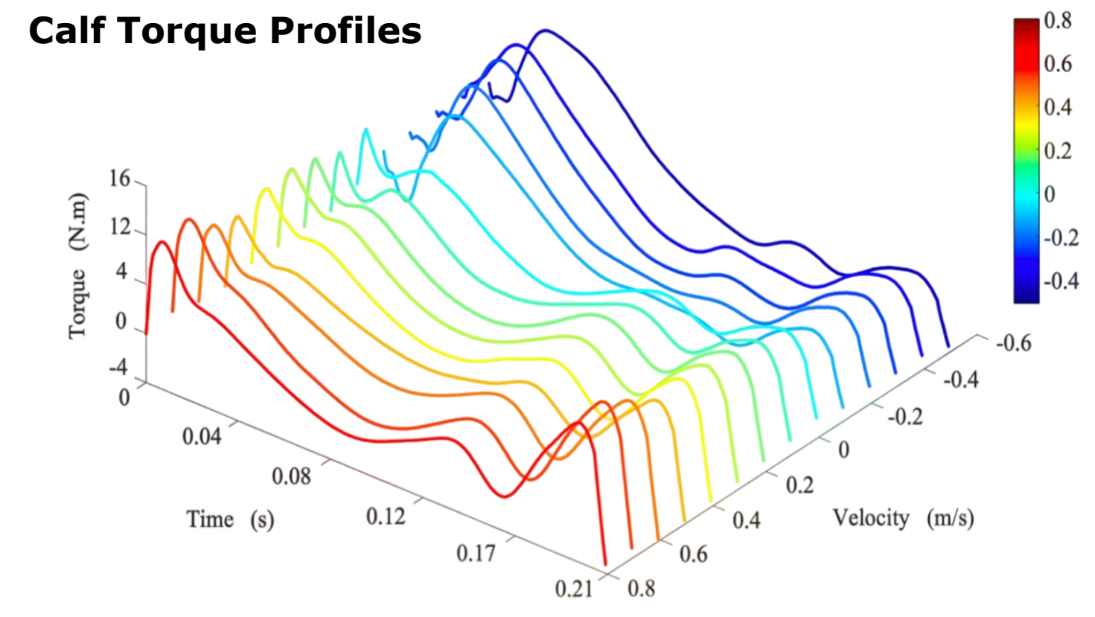
Precise trajectory tracking for legged robots can be challenging due to their high degrees of freedom, unmodeled nonlinear dynamics, or random disturbances. We propose to use **iterative learning control (ILC)** [5] and let a robot learn from its own mistakes by exploiting the repetitive nature of legged locomotion within only a few trials. This process resembles how animals learn their muscle memories in nature.



- Feedback term: $\tau_k^b(s) = K_P^b e_k(s) + K_D^b \dot{e}_k(s)$
- Feedforward term: $\tau_k^f(s) = \tau_{k-1}(s) + K_{PD}^f e_{k-1}(s + \delta s)$



The ILC acts as a feedforward term and continuously learns from the data obtained from the previous iterations to compensate for the system dynamics and external disturbance in the incoming tasks.



A torque library is created as a lookup table so that the robot does not need to repeat calculations. Once the ILC for a specific task is deployed, a robot can continuously learn from its own mistakes in the previous trials and internalizes the synergies of motor commands as a lookup table linked to the specific task.

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[1] Gan, Zhenyu, et al. "Passive dynamics explain quadrupedal walking, trotting, and tölting." Journal of computational and nonlinear dynamics 11.2 (2016).
[2] Gan, Zhenyu, et al. "All common bipedal gaits emerge from a single passive model." *Journal of The Royal Society Interface* 15.146 (2018): 20180455.
[3] Ding, Jiayu, Amit K. Sanyal, and Zhenyu Gan. "Breaking Symmetries Leads to Diverse Quadrupedal Gaits." arXiv preprint arXiv:2303.04857 (2023).
[4] Alqaham, Yasser G., Jing Cheng, and Zhenyu Gan. "Energetic Analysis on the Optimal Bounding Gaits of Quadrupedal Robots." arXiv preprint arXiv:2303.04861 (2023).
[5] Cheng, Jing, et al. "Practice Makes Perfect: an iterative approach to achieve precise tracking for legged robots." arXiv preprint arXiv:2211.11922 (2022).2017, pp. 719–726.

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