Fast Trajectory Optimization for Quadrupedal Walking on Slopes

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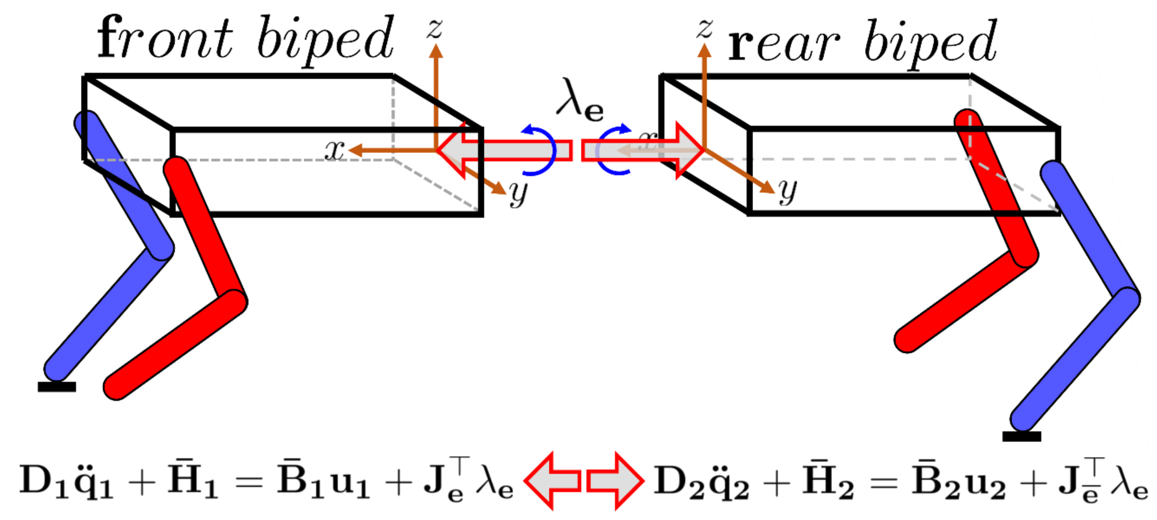
Abstract

- Dimension reduction via the CCS framework leads to faster gait generation
- Experimentally feasible gait generation after 9.7 s and 291 iterations
- Bézier polynomial interpolation provides stable gait transitions
- Optimized gaits are robust to variable outdoor terrain

Coupled Control Systems (CCSs)

$$\underbrace{D(q)\ddot{q} + H(q,\dot{q}) = u}_{\text{Full-Order Dynamics}} \Leftrightarrow \underbrace{\begin{cases} D_i(q_i)\ddot{q}_i + H_i(q_i,\dot{q}_i) = u_i + J_{h_i}^\top \lambda \\ \text{s.t.} \quad h_i(q) = 0 \end{cases}}_{\text{Reduced-Order Coupled Dynamics}}$$



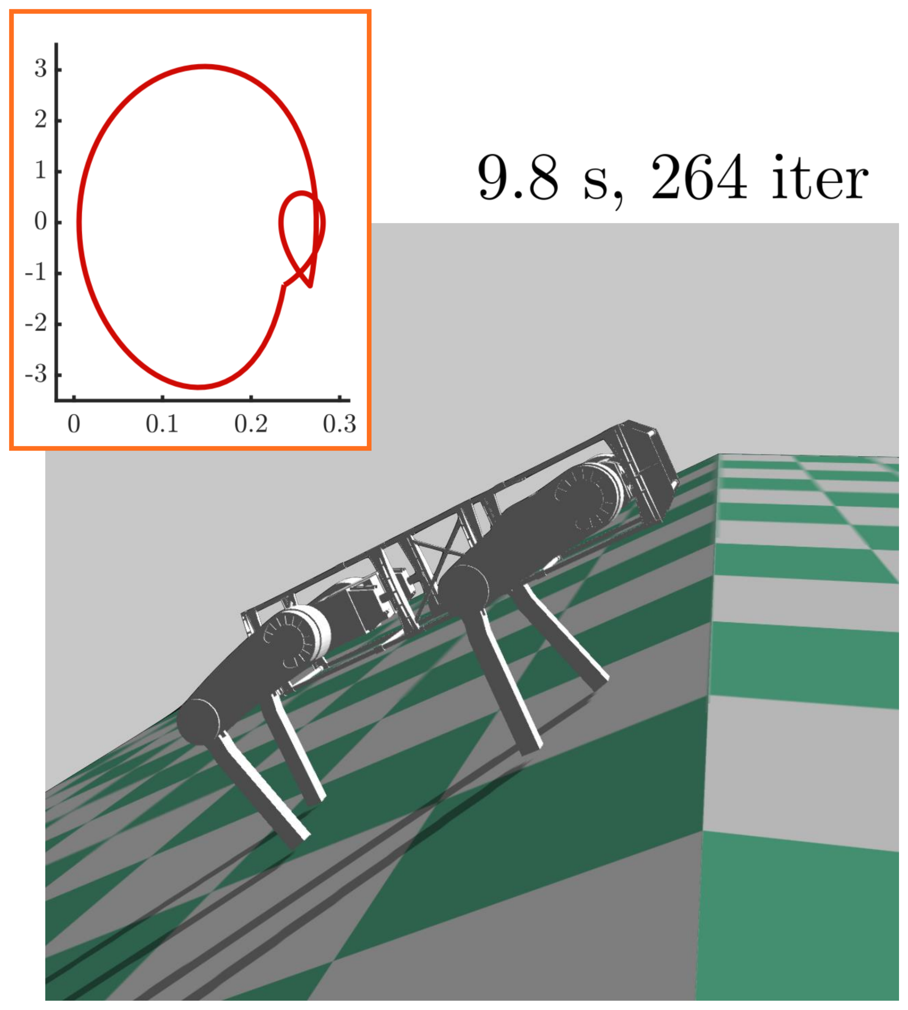
Gait Generation

$$\min_{\{\vartheta^\kappa\}_{\kappa=0,\dots K}} \sum_\kappa \left\|\dot{\xi}_f^\kappa\right\|_2^2 \qquad \kappa = 0, 1 \dots \mathrm{K}$$

s.t. $(C.1)$ dynamic collocation constraints
$(C.2)$ periodic constraints
$(C.3)$ path constraints
$(C.4)$ feasibility constraints

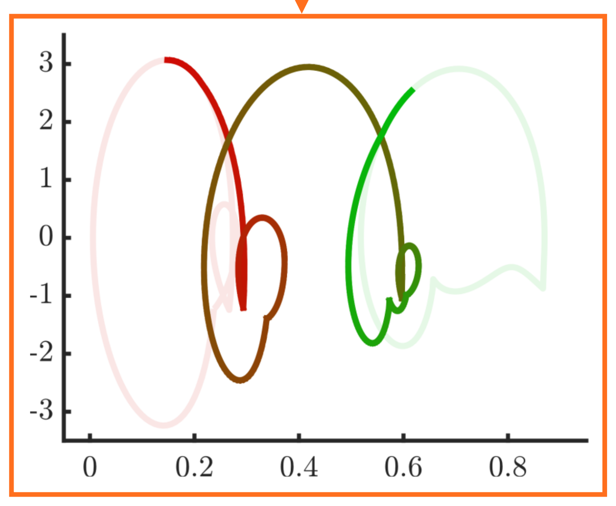
Gait Transitions

$$q_i^d(t) = \mathcal{B}_i(t)$$
$$q^d = (1-\eta)q_{i-1}^d + \eta q_i^d$$
$$u = -k_p(q^a - q^d) - k_d(\dot{q}^a - \dot{q}^d)$$

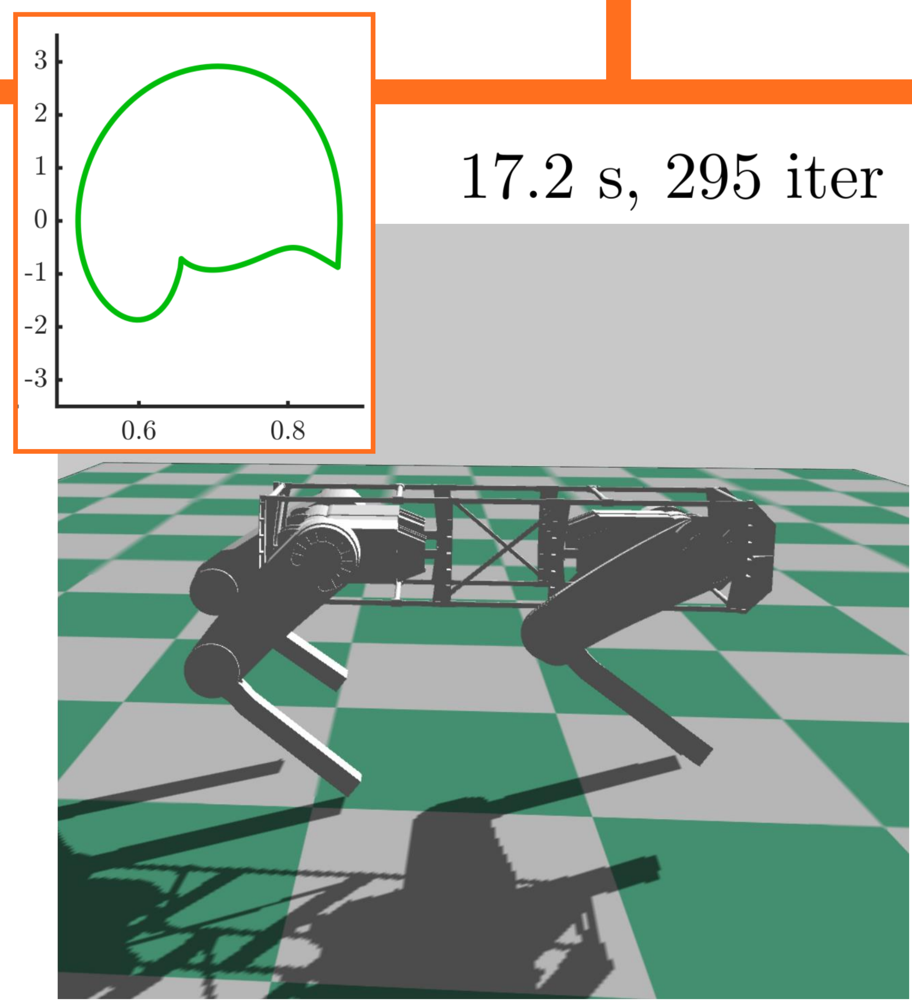


9.8 s, 264 iter

30° Uphill

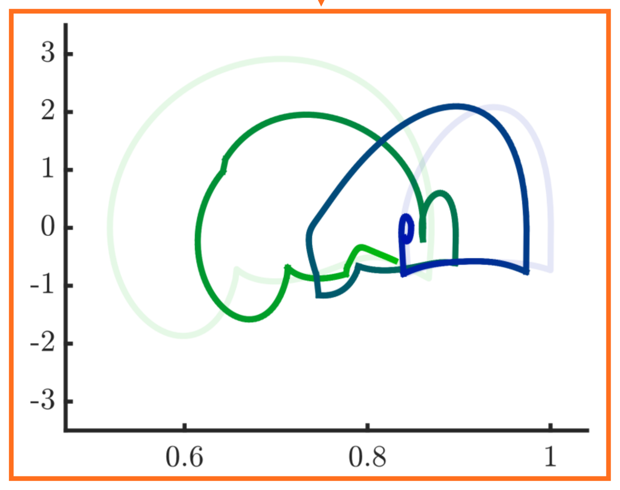


Transition 1

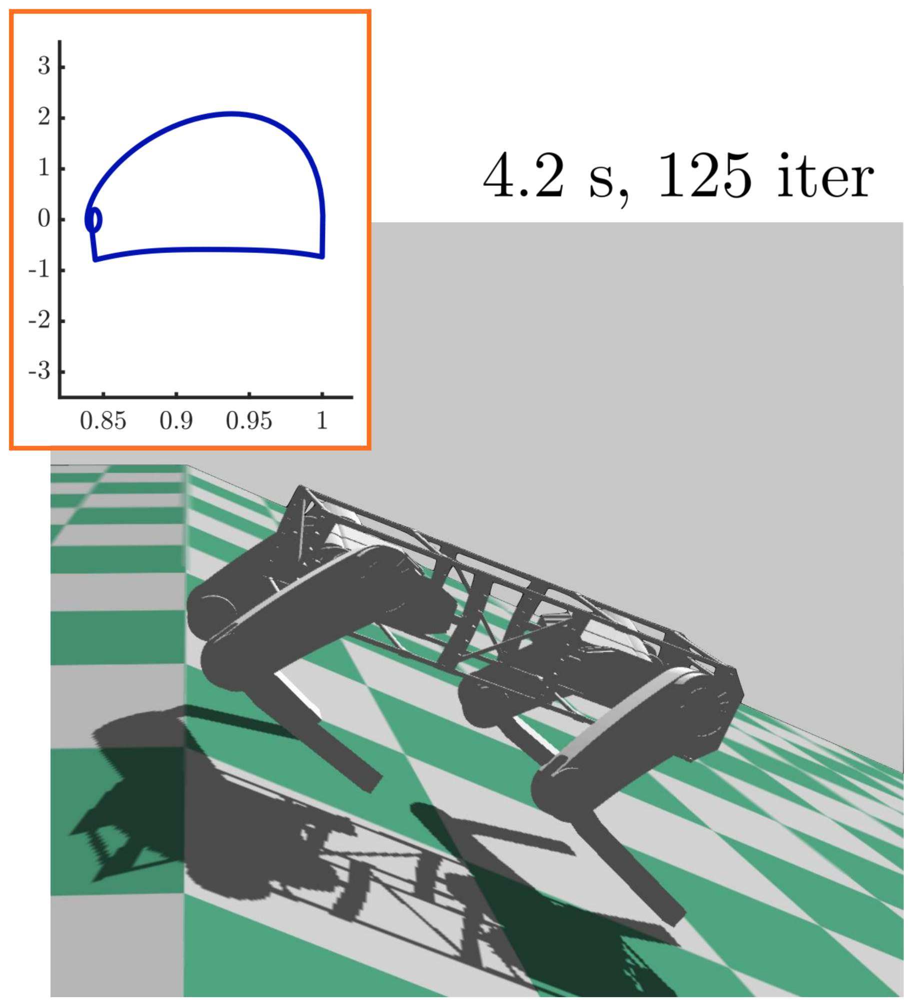


17.2 s, 295 iter

Level Ground



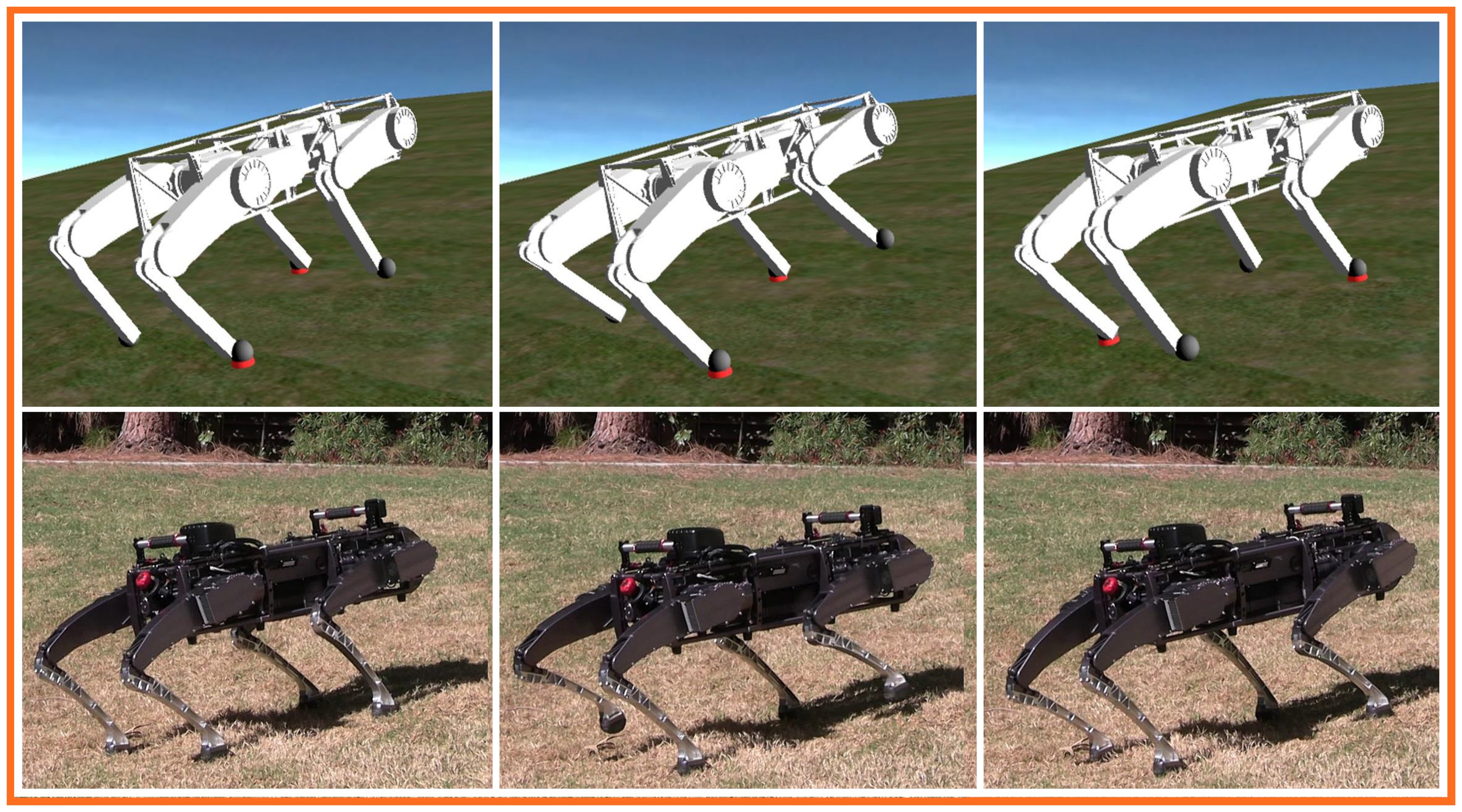
Transition 2



4.2 s, 125 iter

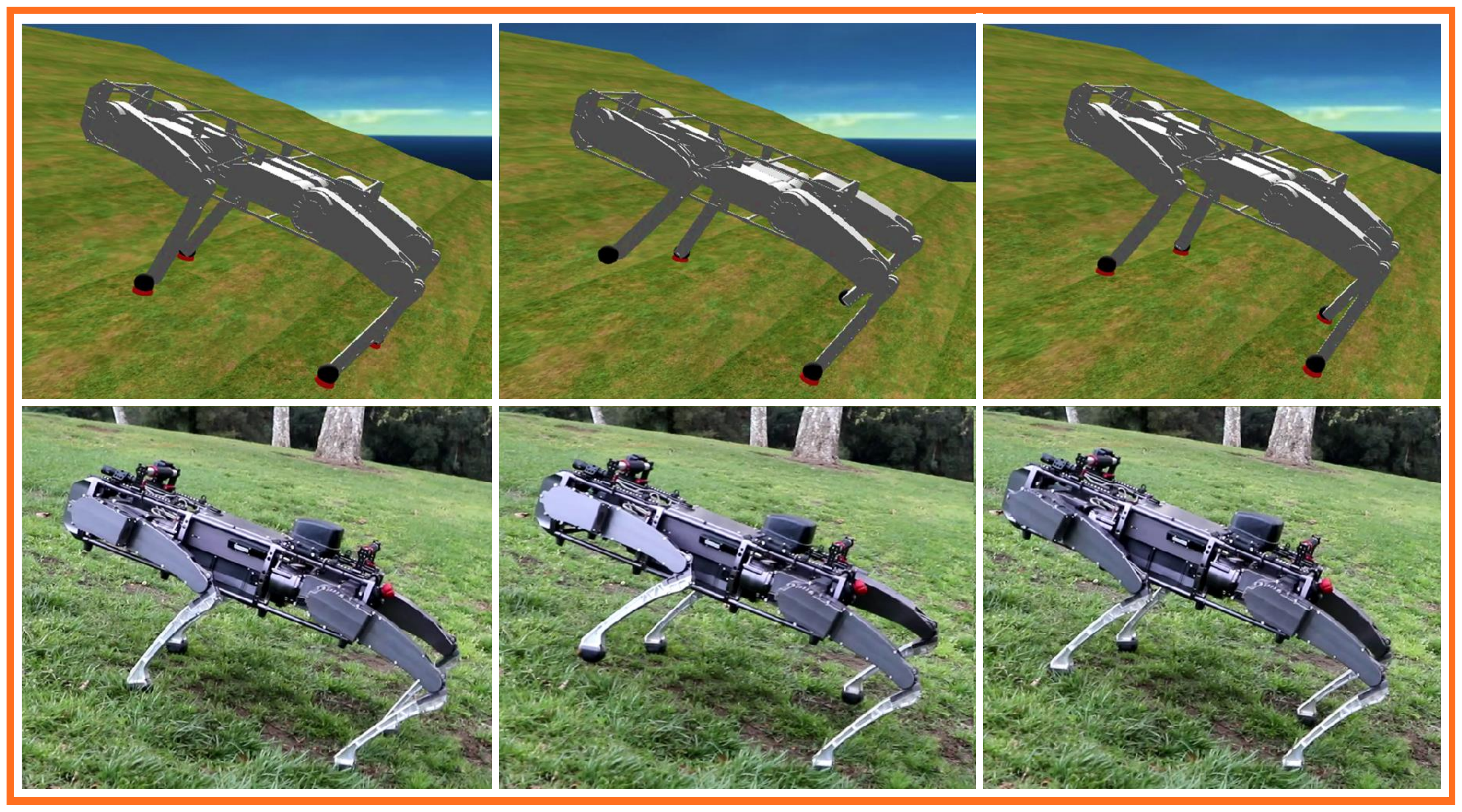
20° Downhill

Outdoor Testing



Walking Outside: https://youtu.be/Cp9XbWkS24U

Simulation



Simulation: https://youtu.be/_xrW1Mc7e0c