Fast Trajectory Optimization for Quadrupedal Walking on Slopes

Noel Csomay-Shanklin, Wen-Loong Ma, Aaron D. Ames
California Institute of Technology
\{noelcs, wma, ames\}@caltech.edu

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

Gait Generation
\[
\min_{\{\theta^*_k\}_{k=0,\ldots,K}} \sum_{k} \left\| \dot{\xi}_k^\kappa \right\|_2^2 \quad \kappa = 0, 1 \ldots K \\
\text{s.t.} \ (C.1) \text{ dynamic collocation constraints} \\
\quad \ (C.2) \text{ periodic constraints} \\
\quad \ (C.3) \text{ path constraints} \\
\quad \ (C.4) \text{ feasibility constraints}
\]

Coupled Control Systems (CCSs)
\[
D(q)\ddot{q} + H(q, \dot{q}) = u \iff \begin{cases}
D_i(q_i)\ddot{q}_i + H_i(q_i, \dot{q}_i) = u_i + J_{\lambda_i}^\top \lambda_i \\
\text{s.t.} \ h_i(q) = 0
\end{cases}
\]

Gait Transitions
\[
\dot{q}_i^d(t) = B_i(t) \\
\dot{q}^d = (1 - \eta)\dot{q}_{i-1}^d + \eta\dot{q}_i^d \\
u = -k_p(q^a - q^d) - k_d(\dot{q}^a - \dot{q}^d)
\]

Outdoor Testing
- 30° Uphill: 9.8 s, 264 iter
- Level Ground: 17.2 s, 295 iter
- 20° Downhill: 4.2 s, 125 iter

Simulation
- Walking Outside: https://youtu.be/Cp9XwWk524U
- Simulation: https://youtu.be/-xW1M7e0E0c