Contact Invariant Trajectory Optimization for Dynamic Quadruped Locomotion

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I. Background

Trajectory optimization is a common tool for planning dynamic behaviors of legged robots. However, the hybrid nature of legged robot dynamics complicates the problem significantly. One approach to this challenge is to predetermine a contact schedule. This makes for the simplest formulation, but greatly diminishes the potential behaviors that can be generated. Other approaches that don't assume a contact schedule, like mixed-integer programming (MIP) [1] or complementarity constraints [2], can generate richer sets of motions, but are far more difficult to solve. An alternative approach, referred to as "contact invariant optimization" [3], attempts to avoid some of the numerical difficulties of MIP and complimentary constraints by, essentially, moving them into the cost function. The resulting optimization is typically easier to solve, but cannot guarantee any degree of dynamic feasibility.

II. Approach

We propose an approach to trajectory optimization that leverages advantages of contact invariant optimization (CIO) while ensuring dynamic feasibility. Our framework includes three separate optimizations that each use the solution of the previous as an initial guess. The first optimization, which ignores the terrain and simplifies the robot's dynamics, generates a rough, task-dependent motion sketch by solving a quadratic program. The second optimization is similar to conventional CIO [3] in that contact constraints are encoded via the cost function, but novel in that we use a single "CIO variable" to describe the gait of the robot, rather than individual variables for each limb. A CIO variable is simply an optimization variable that corresponds to a limb being in or out of contact with the ground. This simplifies the optimization because number of variables involved in the the nonlinear CIO cost function is significantly reduced. However, our approach, like classic CIO, retains the ability to alter the robot's gait and produce motions like jumping over obstacles that could otherwise not be traversed. Since a CIO is not guaranteed to be dynamically feasible, we "clean up" the output of the CIO by translating the CIO variables into a gait schedule. This gait schedule is then used in a simple, fixed-gait trajectory optimization where contact dynamics are enforced as constraints.

III. Results

Our preliminary results show that the approach can efficiently plan motions for the MIT Mini Cheetah over obstacles like hurdles and valleys. For motions with a time horizon of 1.2s and a dynamics timestep of 0.1s, the entire sequence of optimizations typically solves in 0.5-8s on a laptop with an Intel i7 processor, depending on the difficulty of the terrain. About 90% of the time required to plan a given motion is spent in the CIO-like step, and the remaining 10% in the initial QP and the "clean-up" steps. The animation in Fig. 1 shows an example of the framework finding a jumping motion over a 0.3m wide gap. The next steps involved in this work will involve, first, experimenting with solvers that use sequential quadratic programming, rather than interior point methods, that may be better suited for this type of problem and, second, testing planned motions in dynamic simulation.

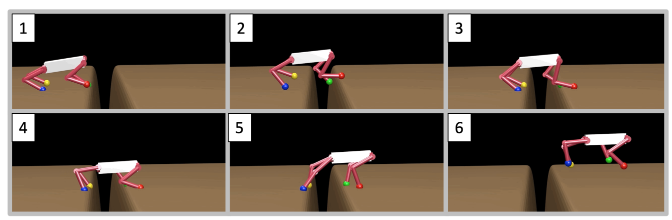

Fig. 1. Planned motion of MIT Mini Cheetah jumping over a 30cm gap.

References

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