Whole-Body Dynamic Planning and Stabilization with Contact

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1 Introduction

As robots impact the ground or the enviroment, the impacts induce discontinuities in both state trajectories and in the governing dynamics. Given the complexity of the impact dynamics, as well as the high degree-of-freedom nature of humanoid robots, approaches to locomotion control and planning are often rely on simplified dynamical models, such as the LIP or SLIP. However, recent advances in both trajectory optimization and convex optimization approaches to real-time control have made it possible to plan and stabilize whole-body motions and reason about the complete system dynamics. Here, we present an approach which generalizes the use of quadratic programming (QP) to control of high dimensional bipedal robots. The resulting controller is expresed in the full floating-base coordinates and is robust to unplanned contacts.

2 Background

Traditional control and planning algorithms have treated impact discontinuities through a hybrid systems formulation, where any particular contact state implies a hybrid mode, and impacts are resolved via hybrid transitions. Enumeration and consideration of every such hybrid mode, however, is computationally intractable for complex robots. Recent work has exploited the complementarity-based formulation of contact that reasons about the integral of contact forces over a discrete time step. We previously introduced an algorithm for contact implicit trajectory optimization, where open-loop trajectories can be synthesized without specifying a mode sequence [4]. We have also explored efficient, convex optimization-based approaches to stabilization of dynamic legged locomotion [3]. The QPs that arise in these problems have structure which we exploit with custom solvers to achieve 1kHz control rates for high-dimensional robots, like the 34-DOF Atlas humanoid.

Recent work has used trajectory optimization and the convex controller to generate complex motions for humanoid robots [1, 2]. However, this approach is limited, in that it does not consider the joint-level system dynamics. Examination of the full system dynamics is required to guarantee that motions respect input limits, or to optimize motions that minimize input.

3 Approach

We first use contact implicit trajectory optimization to generate periodic and aperiodic locomotion trajectories. Since this approach results in coarsely parameterized motions, we apply a secondary optimization as a further refinement stage to improve open-loop accuracy. Given a nominal trajectory, $x_0(t), u_0(t)$, described in the full, floating-base coordinates of the robot, we use a time-varying linear quadratic regulator (LQR), where the state and dynamics are constrained to the active contact manifolds, to compute an approximate cost-to-go $S(t,x)$. State-constrained LQR naturally generates a feedback law and cost-to-go for plants subject to equality constraints, such as the condition that a foot be stationary, and expresses the result in the full, floating-base coordinates. Note that this approach also naturally encompasses closed kinematic loops, such as double-support phases while walking.

While cost-to-go is expressed in the complete coordinates, its value when x is off the planned contact manifold is simply a projection back to the manifold. To use $S(t,x)$ off of the manifold, we reason about potential impacts and augment the cost-to-go with a quadratic approximation of the true distance.

Finally, in real-time, we form a QP that, obeying relevant contact and input constraints, stabilizes the motion along the trajectory by choosing the control output which minimizes the cost-to-go. By exploiting natural distance metrics that arise in rigid body systems, we can augment the QP cost to increase robustness to unplanned contacts, such as when the toe or heel on the foot strikes early or late. We will present simulation experiments with several walking systems including underactuated walkers and a planar Atlas model.

References

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