Running on Ditches and Drops: An Optimization-Inspired Control Approach

Christian Hubicki and Jonathan Hurst

Dynamic Robotics Laboratory
Oregon State University
Corvallis, Oregon

I. Motivation

In the field of dynamic walking, much of the optimal control work focuses on maximizing an attractive basin and reducing energy consumption. However, experiments have noted that birds have a strong inclination to limit peak forces. Peak forces are particularly problematic on potholes and drop steps, where aerial velocities are higher than expected. We seek a control policy that recovers from ditches and drops while limiting peak forces and minimizing energy consumption, a task we will approach using Optimization-Inspired Control.

II. State of the Art

A. Disturbance Rejection

Disturbance rejection is a critical subject of study within dynamic walking. Capture points, which identify viable step-placement regions, have become a framework for recovering from pushes. The robustness of capture points has been demonstrated on both Boston Dynamics' BigDog and the Institute for Human-Machine Cognition's M2V2. While conveniently general, capture points make no explicit effort to minimize energy or peak forces, and as of yet, have only been demonstrated in walking.

Hybrid-Zero Dynamics (HZD) provides a generalized architecture for controlling underactuated, hybrid systems. By numerically optimizing a set of virtual constraints, stable and efficient motion can be generated for high-DOF bipeds. In robot experiments, HZD results in robust running and graceful handling of large drops. To date, HZD has not been used to limit peak forces. We believe a more principled policy can elegantly achieve efficient, force-limited locomotion.

B. SLIP Model Control

The task of controlling the Spring-Loaded Inverted Pendulum is non-trivial; it is nonlinear, hybrid-dynamical, underactuated, and has no analytical solution. Many successful controllers have used intuition and simple insights in order to facilitate control. In particular, we focus on the advancements pioneered by Ernst *et al.* which focus on steady-state, or *equilibrium*, gaits.

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The authors can be contacted by email at:
hubickic@engr.orst.edu

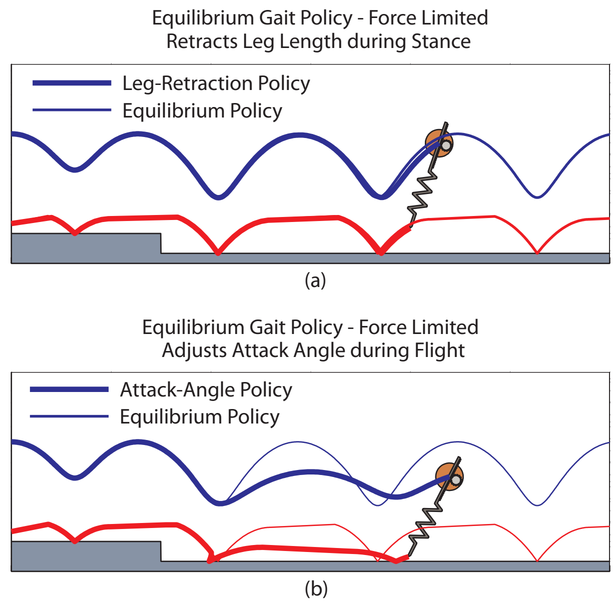

Fig. 1. Simple, principle-based policies for limiting forces on drop steps.

III. Policies and Approach

Motivated by data from guinea fowl, principle-based policies were crafted to limit peak forces. Figure 1a retracts leg length during stance in order to saturate peak forces at a maximum value. Figure 1b steepens the attack angle in response to anticipated large forces. This attack-angle policy results in acceleration of the mass center, an observation also made in birds while on drop steps.

While both policies limit peak forces and prevent falling, they do not necessarily minimize energy costs or return to a "normal gait". We propose an optimal control problem which demands the following. *On a drop step, return to the pre-drop gait within two stance phases while A) limiting peak forces for B) minimum actuator work*. We will present the results of numerical optimizations using Sequential Quadratic Programming and policies derived using an Optimization-Inspired Control approach.

IV. Discussion Questions

- *What environmental knowledge is fair to assume for running robots?*
- *When should we treat terrain as adversarial vs. exploitable?*