Deadbeat Running and Steering in 3D Environments

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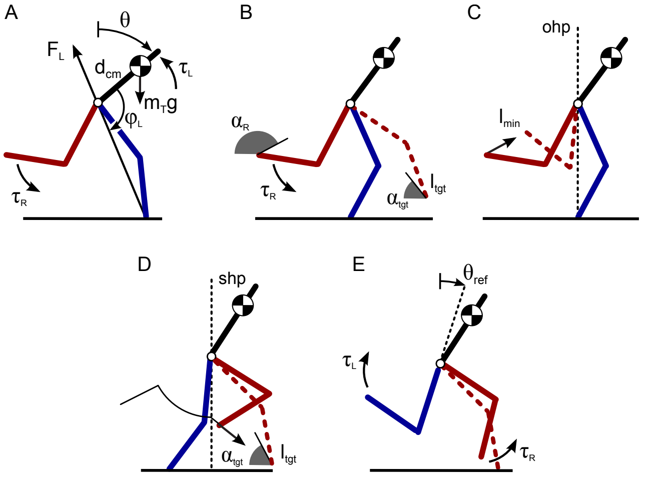

Figure 1: Running model with rigid body dynamics of trunk and legs, series elastic actuation, and continuous contact models.

1 State of the Art and Motivation

Running robots often rely on the spring-mass model as an underlying gait template. The planar version of this model has been widely used to understand the dynamics and control of running [2, 1, 7, 11, 6, 5]. In particular, Poincare analysis has been applied to this dynamic system to control landing angle α (potentially along with spring stiffness k) as a function of flight time after the apex event, thereby achieving dead-beat stability that rejects disturbances in ground height without the need to measure them [10, 3, 4]. While these results indicate that the stability and robustness of running robots can largely be improved with these automatic deadbeat controllers, it remains unclear how they can actually be applied in these machines. The dynamics of running robots entail more behaviors than the abstract spring-mass model can capture with a point mass supported by massless legs. Critical behaviors include trunk balance, swing leg ground clearance, and the motion in 3D. We seek to understand how the control theory developed for the spring-mass model can be extended and transferred to running robots.

2 Our approach

We approach our goal from two directions. First, we simulate more realistic robot models and derive hierarchical control strategies that generate spring-mass-like locomotion while maintaining trunk stability and swing leg clearance. Figure 1 shows a planar running model that includes rigid body dynamics of a heavy trunk and lightweight legs, considers the dynamics and reflected inertias of electric motors that drive the hips, and models the ground interaction with continuous contacts and stick-slip friction. The torque controllers for the motors enforce spring-like leg behavior in stance, balance the trunk in proportion to how much weight the stance leg bears (Fig. 1A-D), and manage the distribution of angular momentum between trunk and legs while prioritizing the swing leg's placement into landing angles (C-E). The landing angle trajectories are derived from the spring-mass model's deadbeat control. Although the biped's physics do not match the spring mass model, we observe robust running without sensing the ground level at running speeds of 5ms^{-1} over rough terrain with random changes in ground height of up to ±15cm (total step size up to 30cm). Here the ground tolerance is primarily limited by the maximum hip torques that the model's actuators can produce.

In the second direction, we generalize the Poincare analysis of the abstract spring-mass model to 3D environments and derive automatic deadbeat controllers for running stability and steering in rough terrain (Fig. 2). The control of spring-mass running in 3D environments has been explored in prior work. For example, [9] analytically show that all left-right symmetric periodic gaits are unstable under constant landing parameters. To locally stabilize lateral motions, the authors introduce a corrective feedback similar to those derived for passive dynamic walking [8]. However, the feedback framework does not generalize the global deadbeat behavior. By including the splay angle β of the swing leg (Fig. 2A) in a leg placement strategy, we show how omni-directional running can be achieved in the spring-mass model with the same deadbeat robustness against variable ground levels as in the planar case [12]. In addition, we show how the control can simultaneously be generalized to steering and demonstrate in simulation the deadbeat stability and disturbance rejection of the three dimensional system as it runs to waypoints over terrain of random height (Fig. 2B).

3 Discussion

Our results suggest that a large portion of the stability and robustness offered by the automatic deadbeat control can be transferred to complex running robots. In particular, a hierarchical control framework evolves, using the Poincare analysis to derive globally stable and robust model behaviors which are then locally embedded in the control of dynamically more complex running systems. While this ap-

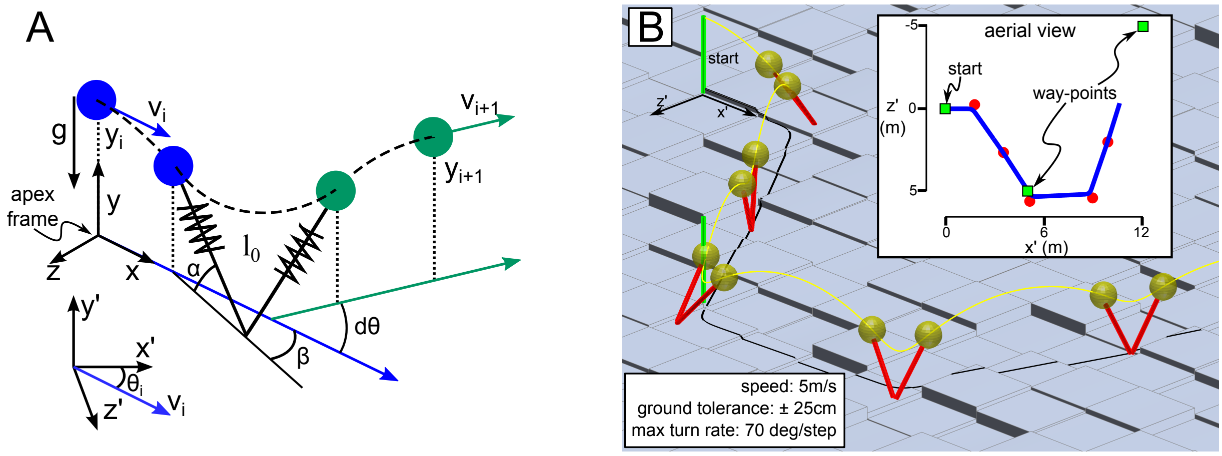

Figure 2: Deadbeat control of spring mass running and steering in rough 3D environments.

proach does not guarantee global stability for high dimensional robotic systems, the deadbeat stability of the underlying gait models suffices to produce highly robust locomotion. In the next step, we aim to combine the two directions and transfer the 3D deadbeat control for running and steering to a 3D system of a running biped.

4 Open questions

A key question that arises from this research is whether the hierarchical approach to gait control can be automatized. Currently, we use intuition about locomotion physics to develop core models of legged dynamics and control that can be studied rigorously. From these underlying gait models, we hierarchically develop new models of increasing complexity that inherit the behavior of the models they embed while addressing additional higher-order dynamics. The progress in this field would be considerably accelerated if we could develop algorithms that capture this intuition and automatically establish the hierarchy of importance.

Preferred Format: talk

Keywords: spring-mass running, deadbeat control, three-dimensional environments.

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