The theory, implementation, and evaluation of spring mass running on ATRIAS, a bipedal robot

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Abstract

We expect legged robots to be highly mobile. Human walking and running can execute quick changes in speed and direction, even on non-flat ground. Indeed, analysis of simplified models shows that these quantities can be tightly controlled by adjusting the leg placement between steps, and that leg placement can also compensate for disturbances including changes in the ground height. However, to date, legged robots do not exhibit this level of agility or robustness, nor is it well understood what prevents them from attaining this performance. This thesis begins to bridge the gap between the theoretical motions of simplified models and the implementation of agile behaviors on legged robots.

The state of the art allows room for improvement at the level of the simplified model, at the level of hardware demonstration, and at the level of theoretical understanding of applying the simplified model to a real system. We make progress on each of these facets of the problem as we work towards leveraging theory from the simplified model to generate effective control for locomotion on robots. In particular, spring mass theory has identified deadbeat stability for planar running, but it must be formulated in 3D to be applicable to a real system. We extend this behavior to 3D, adding deadbeat steering to the tracking of apex height on unobserved terrain. Running robots have yet to demonstrate the agile and robust behavior that the spring mass model describes; existing implementations do not target the deadbeat behavior. We apply state of the art control techniques to map the deadbeat stabilized planar running onto our robot ATRIAS, and we successfully demonstrate tight tracking of commanded velocities and robustness to unobserved changes in ground height. Despite this empirical proof of concept, it remains unclear how exactly the targeted behavior of the simplified model affects the closed loop behavior of the full order system. There are additional degrees of freedom which affect the tracking of original goals and additional layers of control which may offer other sources of stability. Furthermore, the hardware introduces perturbations and uncertainties which detract from the nominal performance of the full order model. To answer these questions, we formulate a framework founded on linear theory, and we use it to examine the contributions of each component of the control and to quantify the expected effects of the disturbances we encounter. This analysis reveals insights for effective control strategies for legged locomotion and presents a tool for scientific iteration between theory-based control design and evidence-based revision of the underlying theory.