Title: Capturability-based Analysis and Control of Dynamic Scrambling with Multiple Contacts on Rough Terrain

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Motivation: Humans and animals effortlessly locomote over rough terrain quickly using multiple appendages and body contacts on surfaces of varying height, surface normal, and texture. We are interested in the fundamentals of such locomotion and how knowledge of the fundamentals can be exploited in the control of legged robots to dynamically locomote on extreme terrain.

State of the Art: The mathematics of static equilibrium with multi-contact is essentially a solved problem with several references. Sentis and colleagues have showed how to plan multi-contact dynamic manuevers. However, we are unaware of results in multi-contact capturability, i.e. answers to the question: given a legged system's state and available contacts, can the system prevent a fall by taking n steps or fewer, and if so, what is a control policy which would achieve preventing a fall?

The main barrier to such analysis and control is computational complexity. Answering such capturability questions is conceptually easy and can be formulated as a large dynamic programming problem. However, in general, solving such problems become computationally hard.

Our Approach: Our approach is to find simplifying assumptions which reduce the computational burden, yet do not change the fundamentals of locomotion. In our past work the simplifying assumptions we used were that the center of mass remained at a fixed height, that the angular momentum available for "lunging" and "windmilling" could be modeled as a single flywheel-like inertia, and that the ground was flat with no slipping. With these 3 assumptions, "n-step capture regions" for any n could be easily computed with trivial computational burden, and control strategies based on manuevering an "instantaneous capture point" from one n-step capture region to the next could be developed.

Current Results: In our current work, we have relaxed the assumption of flat ground with no slipping and instead use multi-contact models which include surface normal, varying heights, and friction constraints. These constraints can be formulated as convex feasibility constraints on the net wrench on the legged system. The constraints are second-order cone constraints, but can be further simplified to linear constraints by approximating the friction cone as a polyhedron. Convexity of the contact constraints allows us to explore the fundamentals of multi-contact legged locomotion. As one example, we can define a convex three dimensional effective support polytope from which the effective ground reaction force can emanate. We can also solve various capturability questions quickly and efficiently. As one example, a sufficient condition for zero-step capturabilty is whether the "instantaneous capture arc" (the curve of instantaneous capture point as a function of height above the ground) passes through the effective support polytope.

Best Possible Outcomes: If our approach pans out we will: a) define geometric entities which have the same power and intuitive meaning as their flat ground counterparts, such as "support polygon", "center of pressure", "centroidal moment pivot", and "instantaneous capture point", b) better understand the fundamentals of humans performing Parkour or mountain goats running on ledges, and c) develop algorithms for determining where and how to step or place a handhold and how to exploit internal angular momentum in order for legged robot to perform similar feats.