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Dynamically Diverse Legged Locomotion for Rough Terrain

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Abstract— **In this video, we demonstrate the effectiveness of a kinodynamic planning strategy that allows a high-impedance quadruped to operate across a variety of rough terrain. At one extreme, the robot can achieve precise foothold selection on intermittent terrain. More surprisingly, the same inherently-stiff robot can also execute highly dynamic and underactuated motions with high repeatability. This range of dynamic motion is possible through careful reasoning about the coupled dynamics during underactuated phases of motion. Our results demonstrate visceral progress toward realization of one of the central theoretically claims giving legged locomotion a "leg-up" over wheeled robotics: that appropriate design of control can produce a set of capabilities which span a dynamic range from deliberate foothold selection through acrobatic-style motion on a single, particular robot.**

I. INTRODUCTION

A goal for legged robots is an adaptability to terrain comparable to that legged creatures in nature: ideally, legged locomotion should exploit both careful foot placement and more dynamic motions, as appropriate to the terrain. However, achieving both simultaneously in a single robot is a challenging task. While animals walk and run over incredible terrain with apparent ease [7], often leaping from one foothold to the next, many of our robots move slowly and methodically, constrained by overly restrictive measures of dynamic stability. As described by [5], what we strive toward as roboticists are "dynamically dextrous robots".

The amazing dynamic capabilities of biological systems are often attributed to their use of compliant joints, which permit energy storage (and fast release) and provide a level of mechanical robustness. The mechanical design of low-impedance walking robots is one important approach toward achieving dynamic gaits [9]. By contrast, our work here explores solutions involving only control. In particular, we develop a motion-planning algorithm which allows a stiff, position-controlled quadruped robot to execute reliable dynamic maneuvers that are often associated with more compliant systems. By reasoning about the ground reaction forces and the dynamics of the passive degrees-of-freedom between the feet and the ground, we are able to design trajectories of the center of mass which maneuver the robot into and through a "bipedal" double-support phase.

Robots with exceptional capabilities on stochastically rough terrain, such as RHex [1], are typically incapable of careful foothold selection. By contrast, implementations which aim toward precise foot placement often traverse terrain by using relatively slow, deliberate gaits [3], [4], [10], [8], [6]. In this video we demonstrate a control approach which can achieve *both* precise foot placement, as illustrated in Figure 1, and highly dynamic and fast motions, such as the lunge shown in Figure 2.

Fig. 1. LittleDog demonstrates careful foot placement.

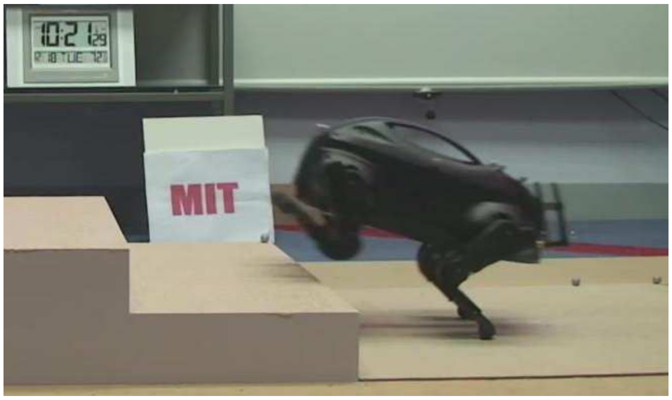

Fig. 2. LittleDog exploits underactuated, dynamic motions to climb a step.

II. EXPERIMENTAL HARDWARE

The LittleDog quadruped has an approximate mass of 2.4 kg and 18 degrees of freedom (DOF): 12 actuated leg joints, plus the 6 (underactuated) degrees of freedom of body. Planning for desired joint trajectories is done on an off-board computer; a low-level PD control loop onboard the robot regulates the joints. Joint commands are actuated through high gear-ratio transmissions (84:1), giving them high impedance to external disturbances. Rounded feet on the dog allow for no achievable ankle torque, so the support legs become unactuated during double-support motions.

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The robot operates in a motion capture (mocap) environment, to estimate the 6 DOF of the body and to detect upcoming, scanned terrain boards.

III. Methods

When precise footholds are require, as in Figure 1, we plan statically stable poses for the robot and execute them slowly. Underactuated motions such as the dynamic lunge in Figure 2 are planned using low-dimensional, planar models, as depicted in Figure 3. The two components of force (in x and z, only) generate both two corresponding translational accelerations and a rotational acceleration. To produce feasible and repeatable kinodynamic plans, we reason about the physically achievable joint velocities, the ground reaction forces, and the inherent effects of stochasticity on the dynamics. Our results demonstrate low variability in the peak angle achieved during a lunge. In crossing a gap, for example, the peak pitch angle of the robot has a mean of 24.6° with a standard deviation of less than one degree.

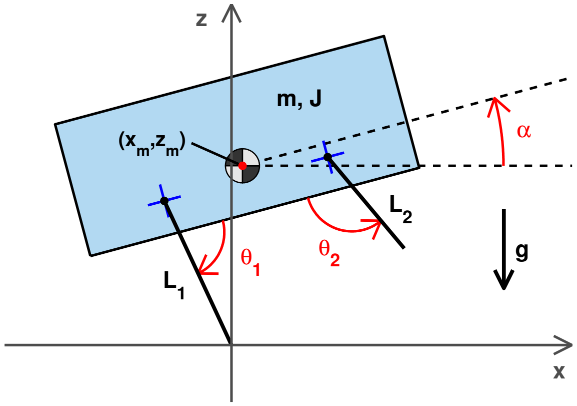

Fig. 3. Planar model of the robot during a dynamic lunge.

IV. CONCLUSIONS

In the accompanying video, we demonstrate a range of dynamic behaviors for a particular legged robot. At one extreme, careful motions of the high-impedance robot allow for precise foothold selection. To achieve faster locomotion on appropriate terrain with high reliability, we reason about the inertial coupling between actuated and unactuated degrees of freedom during phases of underactuation. Some of the results demonstrated here are discussed in more detail in [2].

V. ACKNOWLEDGMENTS

Our work on dynamic motions for LittleDog owes much to the entire MIT Team in the Learning Locomotion project. Particular recognition is given to Alec Shkolnik and Sam Prentice, who have made heroic contributions in developing code for autonomous control of LittleDog throughout Phase 2 of the project.

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