Massachusetts
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Motion Planning for Dynamic Quadrupedal Locomotion on Extreme Terrain

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Dynamic feasibility for underactuated locomotion

We have designed repeatable double-support motions for a stiff, (non-compliant) quadruped* enabling fast locomotion across terrain features including ditches (negative obstacles) and tall barriers. These double-support motions, in which only two of the four legs touch the ground, are underactuated and must be designed respecting dynamic compatibility of the modeled degrees of freedom. Additionally, performance should be robust to variations in initial conditions or in particular robot parameters (such as backlash, which is increases over time as a robot ages).

Our design approach uses simple models of the robot as a planar system (Fig. 1) and results in open-loop trajectories lasting on the order a half a second to several seconds. Each dynamic motion begins close to a particular, desired initial state. We stitch together motions by generating stance-correcting trajectories after a motion is complete. The result produces acrobatic motions with impressive repeatability and speed.

Fig. 1: Planar models of the robot

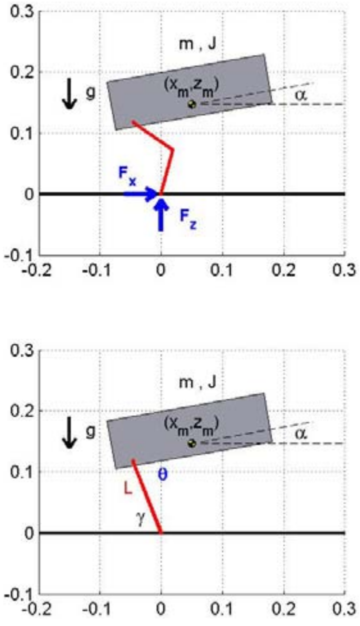


Fig. 2: LittleDog in a dynamic climb

Modeling open-loop double-support motions

Figure 1 shows two basic 2D models we use to capture the dominant dynamics of a double-support motion such as a “dynamic climb” (shown in Fig. 2). In each case, the robot is modeled as a brick-like body of mass *m* (2.2 kg) and inertia J_y (0.028 kg-m^2), with a single point of contact (x=0, z=0). At top in Fig. 1, we consider only the ground reaction forces at this contact point, ignoring leg length (which may adjust within kinematics limits of the robot). These two forces affect all three degrees of freedom: x_m and z_m of the body and its global angle, α:

$$\ddot{x}_m = \frac{F_x}{m} \qquad \ddot{z}_m = \frac{F_z - g}{m} \qquad \ddot{\alpha}_m = \frac{(F_z - g)x - F_x z}{J}$$

Sensitivity to initial conditions

This model produces qualitatively satisfying results which agree well with data when properly tuned (Fig. 3). However, commanding forces directly yields model results which are very sensitive to initial conditions. The lower model in Fig. 1 better captures how open-loop commands are executed on the actual robot. Here, we assume the leg remains at a constant effective length, *L* (0.175 m), and that only the leg-body angle θ is regulated (using a PD controller to track the desired actuated angle over time, while ignoring the underactuated angle entirely). This model accurately reflects the reduced sensitivity of the actual robot to command of the actuated joint over time, as compared with sensitivity of the initial model used in trajectory design.

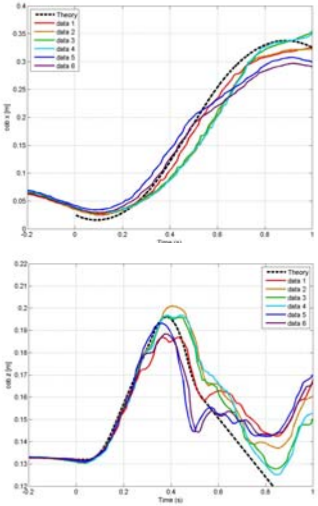


Fig. 3: Model theory vs actual robot data in x_m (UpL), z_m (LowL) and α (UpR). Bottom: Force inputs in x and z .

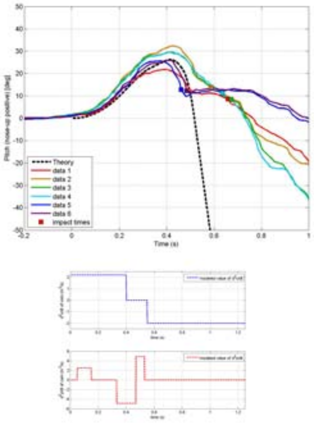


Fig. 4: Sensitivity to initial conditions for the force model (left) is much greater than for the leg-to-body angle model (right). Joint position trajectories from the force model can be played out on the stiff robot to produce repeatable results, as predicted by this second, more robust model.

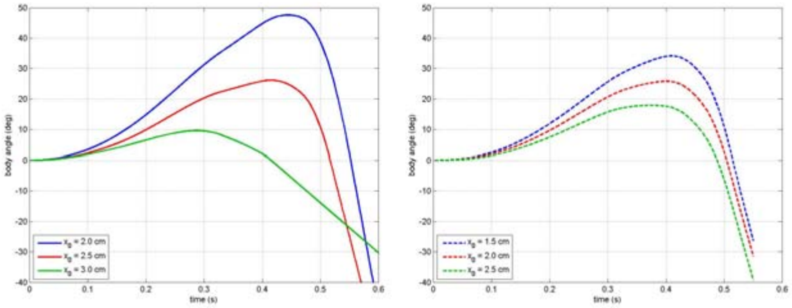
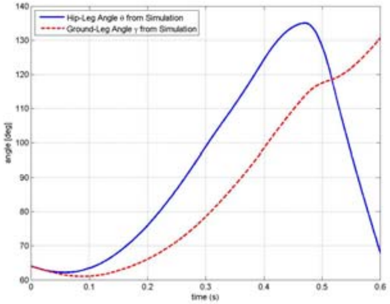


Fig. 5: leg-to-body (aka “hip”) angle in solid blue is the actuated command trajectory. The difference between this angle and the ground-to-leg angle (red dashed line) is the global body pitch upward.



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* The LittleDog robot is designed by Boston Dynamics for DARPA’s Learning Locomotion project.