The Energetic Effect of a Flexible Spine in Quadrupedal Robots

Yevgeniy Yesilevskiy, William Yang, and C.D. Remy
University of Michigan
yevyes@umich.edu

Summary

In nature, quadrupeds make significant use of their flexible spine to achieve energetically economical locomotion. We hypothesize that a flexible spine will also be energetically beneficial for robotic quadrupeds. To test this hypothesis, we compare the energetically optimal motion of a model of a rigid spine quadruped to a model with an articulated spine. We look at a variety of common quadrupedal gaits and find that the articulated model experiences significant energy savings over the rigid model at high speeds. The energetic savings are particularly pronounced for galloping.

Introduction

Moving in an energetically economical manner is one of the primary motivations for animal locomotion [1, 2, 3, 4]. Within their chosen locomotion patterns, animals exhibit a complex range of dynamic motions. A particular observation in the motion of quadrupeds, such as cheetahs and horses, is the extension and flexion of their flexible spine. This spinal motion is particularly pronounced during high speed gaits such as galloping. Hildebrand [5] hypothesized that the flexibility allows for longer stride lengths, attributing to the cheetah's high maximum velocity. Alexander [6] built upon Hildebrand's hypothesis when examining various models of quadrupedal animals and suggested that the flexible spine could act as an additional elastic element to store and release energy, and that it could also improve leg recirculation. All three of these factors are possibilities for why a quadruped with a flexible spine is able to move energetically economically at high speeds.

These studies of flexible spines in nature show promise that a flexible spine may also improve locomotive energetics in robots. Our work seeks to establish and quantify the benefits of an articulated spine in a quadrupedal robot. To approach this problem, we compare two quadrupedal models, one with a rigid main body and one with a segmented body composed of two rigid bodies connected by a rotational joint at the center of the torso (Fig. 1). These models are based off our previous quadrupedal robot, StarlETH [7], and are similar to the model in our previous studies

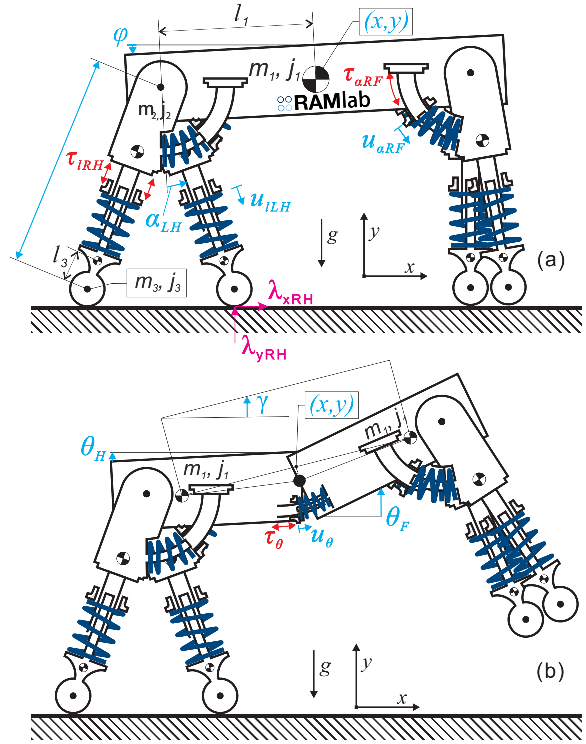

Figure 1: In this work we compare the energetically optimal motion of a robotic quadrupedal model with a rigid spine (a) to a model with an articulated spine (b) to see the energetic effects of a flexible spine.

[8]. These models incorporate complexities such as feet with mass, which introduces collision losses, as well as inertia in the legs and torso. The models also include detailed series elastic actuator models with realistic limitations on motor torque and speed, as well as springs with damping. The complexities in these models allow for physically realistic motions across a wide range of velocities and gaits.

Methods

In order to ensure that we are comparing the most energetically economical motions of each robotic model, we utilize optimal control. Similar to our previous work [8], we used optimization to generate an energy cost landscape for both models using the positive mechanical motor work per distance traveled as a cost function.

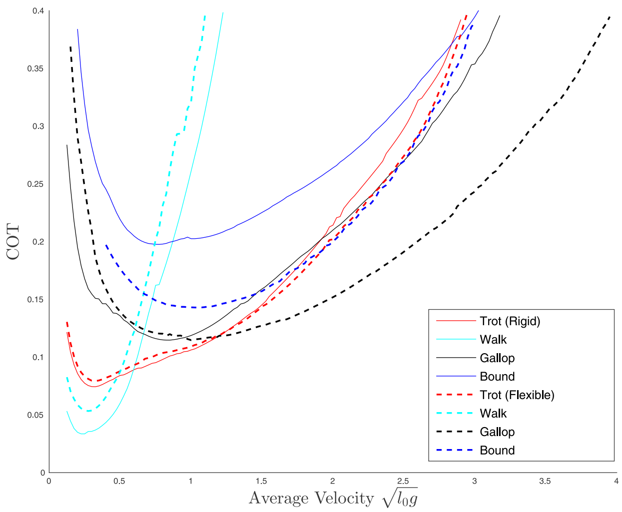

Figure 2: The combined energy cost landscapes of both the rigid model and flexible model for different gaits and speeds. The combined curves show a distinct energetic benefit for galloping with the flexible model at higher speeds.

The positive mechanical cost of transport is defined as:

$$\mathbf{COT} = \frac{\int_0^{\mathbf{t_{end}}} \sum_{\mathbf{i=1}}^{\mathbf{p}} \mathbf{max}(\tau \dot{\mathbf{u}}, \mathbf{0}) \mathbf{dt}}{\mathbf{x}(\mathbf{t_{end}}) - \mathbf{x}(\mathbf{t_0})} \quad (1)$$

Where τ is the motor torque, $\dot{u}$ is the motor speed, p is the number of joints, and the denominator is the distance traveled. We then compare the most energetically economical motion for each of the two models across a range of gaits and velocities.

The constrained optimization problem was solved through a multiple shooting optimization framework (MUSCOD) [9] with methods illustrated and detailed in [8]. In all cases, we examined locomotion velocities between 0.0 $\sqrt{l_0 g}$ and 4.0 $\sqrt{l_0 g}$. For each gait, we conducted an initial optimization at an initial velocity and iteratively conducted optimizations at neighboring velocities in a branching method until the full range of velocities was covered. In this process, we used previously obtained solutions as the initial conditions of the neighboring velocities. At each particular velocity, the solution with the lowest cost was taken as the optimal motion.

Results & Discussion

We find that the articulated model is considerably more energetically economical at high speeds than the rigid model (Fig. 2). This result holds particularly true for galloping. Whereas for the rigid model, there is little energetic difference between galloping and trotting at high speeds, for the flexible model, galloping is overwhelmingly the energetic favorite. At low speeds, as can be seen for walking, the rigid model is slightly more economical, indicating that the benefits of the flexible spine manifest themselves at high speeds.

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