The Effect of Spine Morphology on the Motions and Energetics of Quadrupedal Robots

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Summary

Current quadrupedal robots are capable of complex motions and have sophisticated limb and actuator designs; however, the main body is still typically composed of a single rigid segment. In contrast, quadrupedal animals have noticeable flexion and extension in their spine when locomoting at high speeds, which is hypothesized to reduce their energetic cost. Although several robots have incorporated this consideration in their design, there lacks compelling justification for any particular design. This work seeks to bridge the gap between the current simplistic single joint models of an articulated spine being explored through simulation with the wide range of different spine morphologies implemented in hardware. In particular, this work seeks to quantify the benefits of different spine morphologies to better inform design decisions.

Introduction

In nature, quadrupedal animals utilize their flexible spines to improve their energetic economy [1, 2]. In the submitted abstract "The Energetic Effect of a Flexible Spine in Quadrupedal Robots", we saw that a flexible spine with a single articulated joint can also lead to energetic improvements in robotic quadrupeds.

However, our model of the articulated spine, which was represented as a single actuated joint in the center of the torso, has several limitations. First, the single joint spine contrasts highly with the multi-segmented spines found in quadrupedal animals. Additionally, the section of the spine that undergoes flexion and extension varies between species; for example, the cheetah incorporates the entirety of its lumbar spine whereas a horse restricts sagittal flexion to the lumbosacral region of its spine [3]. Neither of these properties are captured in our current representation of the spine, which motivates the exploration of more detailed spine morphologies.

Several existing quadrupedal robots have implemented various spine morphologies. Zhao and Ellengerber [4] developed Renny which incorporated a configurable spine composed of four pneumatic artificial muscles, whereas Haynes [5] developed Canid with an actuated spine composed of a carbon fiber leaf spring. In simulation, Haueisen [6] looked at a purely rigid model with a single rotational joint, and Cao and Poulakakis [7] explored a model that included elasticity. Koutsoukis [8] examined a linear spring as opposed to a torsional spring; however, again was limited to just a single joint. The high number of different spinal morphologies in hardware, as well as the complexity of each implementation contrasted with the single joint spines being explored through simulation is evidence of a lack of theoretical justification for spine designs.

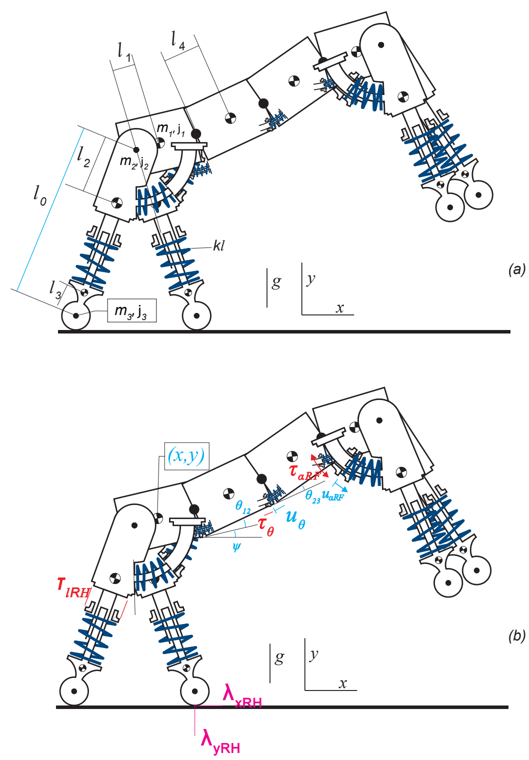

Figure 1: In this work we explore the energetic effects of various spine morphologies on a robotic quadrupedal model. This figure shows the system parameters (a) and generalized torques and coordinates (b) for a 4-segment model. This work will explore models ranging from one to six-segments.

This work seeks to quantify the benefits and differences between the simple, single joint models of a flexible spine from simulation with the complex, high variety spines from hardware through systematically iterating through spines with a varying number of joints and geometries and comparing the energetics of each case.

Methods

Using similar optimization methods and models to our previous work [9], we propose comparing the energy cost landscape for various models. These models extend from our previous models, inheriting their complexities detailed in the submitted abstract, "The Energetic Effect of a Flexible Spine in Quadrupedal Robots", and adding a variable number of joints. The increased number of joints allow us to examine different spine configurations such as the number of segments and increased stiffness in specific areas of the spine. To make the model robust and scalable, we define the additional states to be the relative angle between two adjacent segments and the position of the entire model to be located at the center joint (Fig. 1). To compare the most energetically optimal motions of each spine morphology, we utilize optimal control.

The constrained optimization problem is approached using a multiple shooting optimization framework (MUSCOD) [10] with methods illustrated and detailed in [9].

Future Work

We intend to explore the motion and energetics of various spine morphologies, which will allow us to not only quantify the energetic trade offs of each additional joint, but also allow us to potentially examine motions not found in nature. One such motion could be a "zigzag" configuration of the spine formed by alternating positive and negative relative angles. A multi-segmented quadrupedal model also has the potential to inform us of optimal motions beyond those that we observe in nature. This is because animals are constrained by biological processes, such as breathing that requires a rigid rib cage, or even just evolutionary circumstances, that may not be applicable to legged robots.

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