Dynamic Bounding with a Passive Compliant Spine

G. Clark Haynes*, Jason Pusey**, Ryan Knopf***, and Daniel E. Koditschek***
* National Robotics Engineering Center, Carnegie Mellon University, Pittsburgh, PA
** Army Research Laboratory, Aberdeen, MD
*** University of Pennsylvania, Philadelphia, PA

We present preliminary results of modeling a sagittal-plane compliant spine for a running quadruped, utilizing a Lagrangian formulation to simulate a simplified planar model. While various quadruped gaits are symmetric—such as the crawl and trot, both of which exhibit evenly spaced footfall patterns within a stride—the majority of the fastest quadruped gaits—including the bound, half-bound, canter, and gallop—are all asymmetric [3]. Furthermore, typical quadrupedal runners make use of adjustable spines; it is posited that the cheetah can run almost twice as fast as the similarly-sized greyhound due to a superior spine structure [4]. The sagittal plane model presented in this paper incorporates such a spine structure, and provides insight into the stance dynamics of these fast, dynamic, asymmetric gaits.

The spring-loaded inverted pendulum (SLIP) is a common model of the similar dynamics exhibited by biological runners [1], abstracting the specifics of each animal's morphology to a single mass bouncing on a single leg spring [5]. As animals typically use more than a single leg to locomote, multiple legs are often grouped together, producing SLIP locomotion that is twice periodic that of the animal's gait. This occurs for gaits such as the bipedal run, the quadrupedal trot, and the hexapedal alternating tripod. With asymmetric gaits such as the bound and gallop, however, the complex stance dynamics often result in SLIP-like stance dynamics that are singly periodic with the gait. This paper discusses how the stance dynamics of our model, including a compliant spine, can produce such a response. While similar work has focused upon Lagrangian models of quadrupedal bounding [6], the work was performed with a stiff-backed planar model. Other related work has been performed using a commercial simulation package to test a planar quadruped with an active, controlled spine, however it was found that the active spine model consumed more energy to locomote than a similar stiff-backed model [2], thus backing our notion that a spring in the spine is vital to locomotive efficiency.

Our model consists of two legs—a front and a back leg—each essentially a SLIP model by itself, attached via a compliant spine, modeled as a torsion spring at a fixed offset from each leg mass. Figure 1 presents a general (over-parameterized) model and coordinates, however this model is often reduced in the various hybrid states the system utilizes. Due to brevity of this initial submission, we omit specific details of our formulation, but intend to include them in the full extended abstract submission.

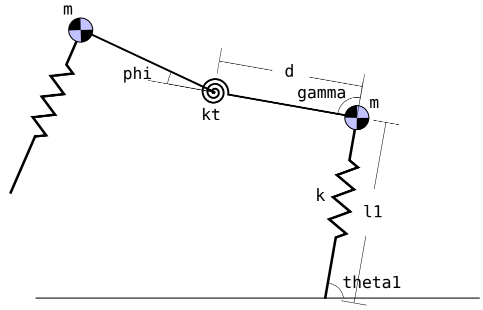

Figure 1: Planar Quadruped with a torsion spring spine. Two masses at each hip interact with the ground via prismatic springs, while an offset torsion spring connects the two masses.

To produce a simulation of this system, a typical Lagrangian approach is taken. We separate the gait into four unique hybrid states, as follows:

- Flight: Ballistic motion while the mechanism flies through the air, consisting of 3 state parameters (x,y) position and rotation, plus their velocities. By design, all springs lie at their rest positions during flight, thus constraining the possible locomotion produced to those that fully unload springs before beginning flight. Furthermore, we treat the spine joint such that a hardstop removes all velocity from the joint and locks the spine when reaching the rest angle.
- Single Leg Stance #1: When a single leg touches down, the system remains 3-dimensional, but with one leg fixed to the ground surface. With a mass-spring not only above the toe (akin to SLIP), but with an additional mass on a lever arm affixed via the compliant spine, the system exhibits unique dynamics.
- Double Stance: With an additional leg touchdown, the system becomes 2-dimensional, with increasingly complex stance dynamics.
- Single Leg Stance #2: Upon liftoff of the first stance leg, the system is once again in single leg stance, a reflection of the previous model, 3-dimensional plus velocities.

The Lagrangian dynamics for each hybrid state are com-

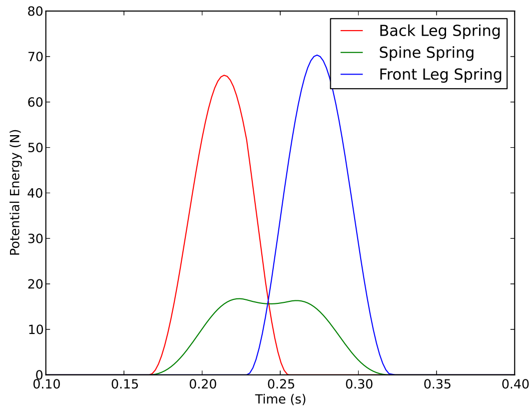

Figure 2: Potential Energy storage in springs during stance

puted analytically using the SymPy symbolic math package[1], exported as source code, and simulated using a Runge-Kutta 4th and 5th order ODE solver from the SciPy project[2]. Full source code of these simulations will be distributed with presentation at the Dynamic Walking conference.

Current results include computation of the stance dynamics when utilizing the compliant joint, for which a video attachment is provided, `canid_preliminary_results.mp4`, however this simulation is still preliminary, with minor fine-tuning to go into it before the full length submission. In Figure 2, we demonstrate how the mechanism is capable of storing energy into the first leg spring and torsion spring during the first stage of stance, maintaining energy in the spine while the leg springs unload and load, respectively, before ultimately unloading both the second leg spring and spine up until the flight begins once again. Currently, this is not yet a limit cycle gait, and the mid-stance point is not a neutral position, as can be noticed in the uneven loading of leg springs, however we expect to produce both of these results before full submission of the extended abstract. The most important current result is the facet of energy storage in the spine, as we input energy to the spine through one leg yet release it through another. As such, it is suggested that the spine may serve a vital role for energy storage and retrieval for high speed quadrupedal running gaits such as the bound and the gallop.

While our initial results focus only upon the stance dynamics of a compliant backbone mechanism interacting with a ground surface, we expect the expanded version of this paper to characterize a variety of limit cycle gaits possible with this simplified quadrupedal model, however this work is ongoing. This will be useful not only to understand the passive dynamic properties of gaits such as the bound and gallop, but also will, with incorporation of the compliant spine, provide simulation evidence of potential styles of locomotion possible for experimental robotic mechanisms that employ active and compliant spine mechanisms.

[1] SymPy: `http://www.sympy.org`
[2] SciPy: `http://www.scipy.org`

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