Quadrupedal Running with Torso Compliance

Ioannis Poulakakis and Qu Cao, University of Delaware, Newark DE

***Abstract*—A variety of conceptual models has been introduced to study legged locomotion. Such models offer unifying descriptions of task-level locomotion behaviors, and inform control design for legged robots. Our work focuses on models for quadrupedal running, with the objective to better understand the effect of torso compliance on gait stability and efficiency.**

Keywords: Reduced-order models, quadrupeds, compliance.

I. Introduction

On a macroscopic level, legged locomotion can be understood through reductive models, the purpose of which is to capture the dominant features of an observed gait without delving into the fine details of a robot's (or animal's) structure and morphology [1]. Restricting attention to running, much of the relevant literature revolves around simple pendulum-based, spring-mass systems, with the Spring Loaded Inverted Pendulum (SLIP) being a representative example [1]. However, the SLIP and its direct extensions cannot capture the leg-torso coordination dynamics that characterize commonly employed quadrupedal running gaits, such as the gallop and the bound. To address this issue, a series of quadrupedal models has been proposed; e.g., [2]. Yet, these models describe systems with rigid, non-deformable torsos. On the contrary, the work presented here focuses on torso flexibility, and on investigating its effects in a template setting.

II. Running Quadrupeds: Modeling and Control

Along the philosophy of the SLIP, our analysis begins with a sagittal-plane quadrupedal model with a segmented flexible torso and compliant massless legs; see Fig. 1. Despite the sensitive dependence of the motion on the torso's bending oscillations, return map studies reveal that a large variety of cyclic bounding motions can be realized passively, through the natural interaction of the model with its environment. Furthermore, for certain combinations of the torso and leg relative stiffness self-stable bounding motions emerge [3].

Next, to examine the relationship between elastic elements within the torso and the energy requirement for maintaining a gait, the basic model is extended to include non-trivial mass in the legs. By comparing the cost of transport with a rigid-torso model with the same leg mass, it is deduced that torso compliance significantly enhances energy efficiency, but *only* when the Froude number exceeds a particular value. Interestingly, this value corresponds to the Froude number at which transitions from trotting to galloping are observed in animals with drastically different morphological characteristics.

The implications of self-stable bounding orbits to control design are also discussed in the context of a hybrid control law that coordinates the torso bending oscillations with the movements of the legs. When the leg mass is considered negligible, a single actuator at the torso is enough to stabilize the four-degree-of-freedom (4-DOF) system, rejecting significantly large disturbances without excessive effort. It turns out that the same principle of coordinating the torso bending movements with the leg hybrid oscillations is sufficient to stabilize bounding orbits in a model with non-negligible leg mass. In this case, however, a swing-leg retraction controller is needed to enlarge the corresponding domain of attraction.

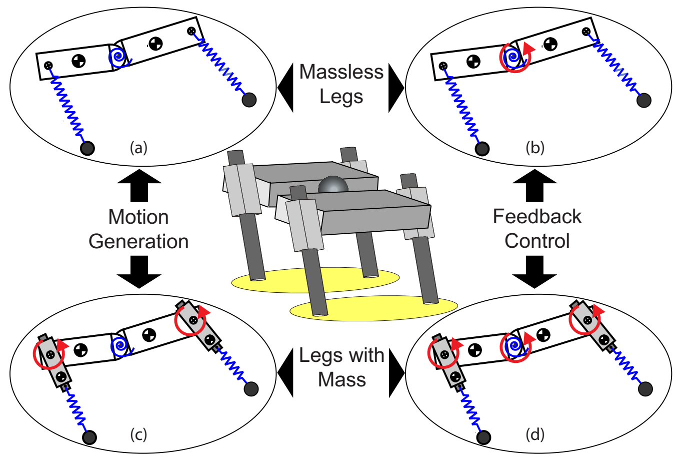

Fig. 1. A hierarchy of models for quadrupedal bounding with a flexible torso. Center: a three-dimensional virtual prototype. (a) An open-loop, energy-conservative template used to generate self-stable motions; (b): The template in (a) with an input toque available at the torso joint for feedback coordination. (c): The template in (a) with non-trivial leg mass and hip actuation to examine the effect of torso compliance on energy efficiency; (d): The template in (c) with a control input at the torso joint to realize stable bounding motions.

III. Conclusions

A hierarchy of models with increasingly varying complexity is studied in an effort to probe the effect of compliance in the torso and legs on the generation, stability and energy efficiency of periodic quadrupedal bounding gaits. These results can be used toward a general framework for designing control laws for robotic quadrupeds with torso compliance.

IV. Acknowledgments

This work is supported in part by NSF grant CMMI-1130372 and ARO contract W911NF-12-1-0117.

References

[1] R. Full and D. E. Koditschek, "Templates and anchors: Neuromechanical hypotheses of legged locomotion on land," *Journal of Experimental Biology*, vol. 202, pp. 3325–3332, 1999.

[2] I. Poulakakis, E. G. Papadopoulos, and M. Buehler, "On the stability of the passive dynamics of quadrupedal running with a bounding gait," *The International Journal of Robotics Research*, vol. 25, no. 7, pp. 669–687, 2006.

[3] Q. Cao and I. Poulakakis, "Quadrupedal bounding with a segmented flexible torso: passive stability and feedback control," *Bioinspiration & Biomimetics*, vol. 8, no. 4, p. 046007, 2013.