

Role of Spine Compliance and Actuation in the Bounding Performance of Quadruped Robots

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1 Motivation

There is so far no quadruped robot that exhibits locomotion performance matching to that shown by animals every day. Both differences in general design concepts, in available materials and actuation mechanisms as well as a lack of understanding on the control of the robots' actuators contribute to the current performance gap between robotic platforms and their biological counterparts. While for example many legged animals actively take advantage of compliant spines for energy storage, maneuverability and achieving energy efficient locomotion with high velocities, most of the existing successful quadruped robots solely exploit the dynamics of their leg mechanics and actuators. From biomechanics studies we know that spine can play important roles in quadrupedal locomotion such as kinematic increase in leg length, providing auxiliary power to the legs and storing and transferring energy [1]. The problem of exploiting these properties in the robotic quadruped locomotion however has not been yet addressed in systematic ways. Complexities arise due to the nonlinear and coupled dynamics of legged systems with compliant and active spines as well as from the trade-off between different performance criteria such as speed, energy efficiency and stability. Studies to gain better understanding can be performed on robots and in simulation. A verification by building and testing robots can provide us with good insights but is time-consuming when many robot morphologies and environmental conditions need to be evaluated. We thus prefer performing extensive studies on the details and parameters of robot and spine morphologies and control in simulation. However, for this simulation studies we need sufficiently detailed mathematical models that can both correctly describe the basic physical properties and capture the dynamics featured by a robot.

In this contribution we introduce novel dynamics model based on existing dynamics modeling approaches [2] that allow detailed studies on the role of a compliant spine in quadruped locomotion. We use this model to address our key questions on locomotion control and the effect of robot morphologies by performing extensive sets of experiments.

2 State of the Art

Most of the existing quadruped robots with dynamic locomotion have rigid trunk and use mostly the natural dynamics of the legs together with different actuation mechanisms in

the leg or hip degrees of freedom. Among those are Raibert's quadruped robot [4], Scout I and II [5], KOLT [6] and BigDog [7]. The role of compliance in the leg design has long been suggested and studied [8]. However there have been few works exploring it in the spine. In the early work of MIT Leg lab [1] the effect of using articulated spine was studied and implemented for a planar quadruped. A finite state machine bounding controller (based on Raibert's control laws) is used to replicate the behavior in which spine is commonly used by quadrupeds such as cats. In a similar approach Culha and Saranlı [9] presented a bounding controller that can increase the forward speed and hopping height of a simulated quadruped by adding spinal joint. They use simple bounding models using SLIP-based leg model and one-DOF spinal joint. The simplified models are good tools for basic understanding of the system behavior, but they are not detailed enough to capture main features such as leg dynamics in swing, actuators dynamics, cost of transportation (modeling the energy dissipation correctly) and stability behavior. Neglecting these aspects increases the gap between simulated results and what can be gained in the reality. Furthermore it makes the transfer of the gained controllers onto robotic hardware difficult. In more complex and realistic models the role of a spine joint in simulated quadrupeds so far has been investigated only for very specific tasks and designs [10]. To the best of our knowledge there have not been systematic and thorough theoretical studies on the benefits of a compliant spine on locomotion performance and on its effect on locomotion control.

3 Our approach to this question

In the scope of a European project called Locomorph, we are studying the role of morphological properties, learning and control on locomotion performance of robots. We study the effect of morphological parameters at different levels; ranging from higher level aspects such as actuation mechanisms to lower level design parameters such as geometrical specifications, mass distribution and stiffness values. One important aspect for us is to explore the effect of adding spine actuation in the design. To this end, the Locomorph robot design has been performed in the way that enables the rapid and easy replacement of the rigid spine with a flexible one. However, since performing experiments on robotic platforms for the exploration of many morpholog-



Figure 2: Snapshots of a sample gait pattern (from left to right) of the developed quadruped model with actuated spine DOF. This sample shows one of the solutions extracted as a bounding gait pattern by the optimization methods. Different sequences of motion can be extracted through the optimization.

ical and control parameters is costly and time-consuming we first aim at extensive simulation experiments that we will verify on the robotic hardware afterwards. We therefore developed a set of mathematical dynamics models for a quadruped robots with rotational spinal joint based on the available methods and tools presented in [2] [3]. Equations of motions are derived based on the Lagrange method and the hybrid dynamics of the system is modeled assuming hard ground contact. Leg masses, trunk inertia, actuators dynamics and energy dissipation are taken into account. Figure 1 shows the schematic of this multi-body model representing the mass points, the joints and the series elastic components. We then use analytical tools like the ones presented by [2] to measure periodicity, stability, cost of transportation and speed of the robot in order to evaluate the overall locomotion performance. Figure 2 shows the snapshots of a sample solution of the simulation experiments (in MATLAB) using the quadruped model with actuated spine. We use stochastic optimization methods to find open-loop gait patterns by optimizing the actuation profiles.

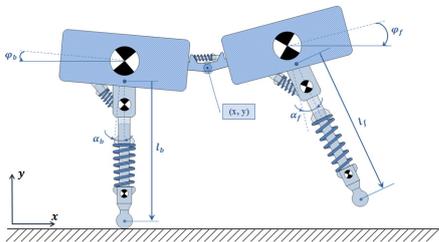


Figure 1: The simulated quadruped with a rotational joint in the spine.

4 Discussion outline

Our goal in this work is to systematically study the effect of morphological and control parameters of a robot on its behavior based on the detailed physical model and the corresponding analytical tools. Even though the simulation results quantitatively cannot be transferred one-to-one to the robotic hardware, they provide valuable insights on the qualitative behavior. We aim at exploring the effect of adding a compliant spinal joint from different viewpoints. The answers to our key questions is highly influenced by the natural and inevitable trade-off between speed, cost of transportation and stability. While expecting performance improvements from compliant spines one should be aware of the existing trade-offs and has to choose design parameter wisely to actually gain benefits from an additional spinal joint. In other words, there might be several ways in which adding

this DOF degrades the performance rather than improves it. Key questions of our study and discussion include *i*-How flexible spine can improve the bounding performance of a quadruped robot (in comparison to rigid spine)? *ii*-What is the effect of adding a *passive* in comparison to an *actuated* spine DOF, *iii*-How does locomotion performance change with the change of stiffness both for the passive and actuated spine? and *vi*-What role do the actuation patterns play in exploiting the spine compliance? In all cases we measure the speed, cost of transportation and stability to gain a meaningful evaluation. Experiments are performed for both cases of passive and actuated spine and for 3 different stiffness values (highly flexible (0.1), flexible (5) and almost rigid (10)). For each setup, 10 runs of optimization experiments are performed using random initialization. We use a stochastic optimization method (PSO) to provide extensive exploration over the search space.

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