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The Merits of Passive Compliant Joints in Legged Locomotion: Fast Learning, Superior Energy Efficiency and Versatile Sensing in a Quadruped Robot

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Abstract

A quadruped robot with four actuated hip joints and four passive highly compliant knee joints is used to demonstrate the potential of underactuation from two standpoints: learning locomotion and perception. First, we show that: (i) forward locomotion on flat ground can be learned rapidly (minutes of optimization time); (ii) a simulation study reveals that a passive knee configuration leads to faster, more stable, and more efficient locomotion than a variant of the robot with active knees; (iii) the robot is capable of learning turning gaits as well. The merits of underactuation (reduced controller complexity, weight, and energy consumption) are thus preserved without compromising the versatility of behavior. Direct optimization on the reduced space of active joints leads to effective learning of model-free controllers. Second, we find passive compliant joints with potentiometers to effectively complement inertial sensors in a velocity estimation task and to outperform inertial and pressure sensors in a terrain detection task. Encoders on passive compliant joints thus constitute a cheap and compact but powerful sensing device that gauges joint position and force/torque, and — if mounted more distally than the last actuated joints in a legged robot — it delivers valuable information about the interaction of the robot with the ground.

Keywords: legged robots, underactuated robots, compliant joints, learning locomotion, force and tactile sensing, haptic terrain classification

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1 Introduction

Typical robot designs feature independent actuation of every Degree of Freedom (DoF), with emphasis on speed and accuracy of movements, which is best achieved if the stiffness of all the components is high. In this domain, the performance of robots has already surpassed that of humans and animals, as demonstrated by the industrial robots in assembly lines, for example. However, these are precisely controlled environments that facilitate the robots' tasks. In unstructured environments, machines are notably lagging behind animals. The same strategy that is applied in manipulators — precise modeling and centralized control of robot and interaction with environment — faces numerous difficulties: contacts with the environment, which are not confined to the end-effector anymore, are hard to sense and model, and the forces that arise cannot be absorbed by a stiff structure in the long run. Animals, on the other hand, do not seem to execute trajectories prescribed by a central controller; instead, behavior is an outcome of the interaction of several components: the mechanical properties of the animals' bodies interacting with the environment, low-level decentralized spinal control, and, finally, the signals descending from different brain areas. During rapid locomotion, the delays in signal transmission preclude direct feedback control exercised by the brain[1] — the main part thus needs to be offloaded to the properties of the muscle-tendon system: compliance, damping, and nonlinear response characteristics in general facilitate successful locomotion and even rejection of disturbances. Mechanical feedback loops, or self-stabilization[2–4], play a key part and make fast and stable, yet not centrally controlled, behaviors possible. The fact that no trajectories are prescribed and enforced, but negotiated between all the interacting components, is

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also responsible for the superior energy efficiency (which is further increased by elastic energy storage in compliant elements).

This viewpoint has been picked up in robotics and informed the design of robots featuring in the extreme case no control at all (passive dynamic walkers[5]) or simple, often open-loop or reflexive controllers only (*e.g.*, Refs. [6–8]). The active descendants of the passive dynamic walker[7] capitalized on the energy efficiency thanks to the exploitation of passive dynamics (demonstrating similar energy consumption to humans). In quadrupedal locomotion, a number of models have been developed, for instance[9–11]; the model of Ref. [12] has been transferred to a real robot as well. Finally, these insights have flowed into the design of successful robots like the Scout II[13] or the Cheetah-cub[14] that exhibit high speeds with very simple control. Previous work leading to the design of our platform, the Puppy (Fig. 1), was motivated by similar considerations, in particular self-stabilizing properties[15]. Like the Scout II, Puppy is strongly underactuated with only one actuated DoF per leg: shoulders/hips (hereafter simply hips) in the sagittal plane. While the Scout II has linear passive compliance in every leg, Puppy's legs have two segments; the "knees" are passive and pointing backward and a spring is attached across these joints. In Ref. [16] we have reported preliminary results on a variety of gaits that the real Puppy robot can display (walk- and crawl-like gaits, turning on spot, pacing, *etc.*). This line of research has produced dynamic robots with unprecedented speeds and energy efficiency, together with simple controllers. However, at the same time, they inherited a strong dependence on the environment and limited diversity of behaviors. Hand-tuned controllers for a single behavior have been often symptomatic of such bio-inspired designs (see Ref. [17] for a survey). The versatility or diversity seems to be further constrained if the robots are underactuated (the following studies address this trade-off and the design of appropriate robot morphologies: Refs. [8,18,19]). Also, since the control is minimally relying on models, the control policies are often determined through ad hoc tuning or expensive optimization procedures (*e.g.*, Refs. [14,20–22]). One of the goals of this work is to demonstrate that these are not intrinsic limitations of the approach.

At the same time, another potential in passive compliant joints, which has not been fully exploited, is that mounting a simple potentiometer on them gives rise to a powerful sensor. The sensor naturally acts like a classical encoder and delivers information about the angle of the joint. However, since the joint is passive compliant, it can be also used to sense the torque at the joint, and, indirectly, the loads further up and down the kinematic chain, thereby carrying rich information about the interaction with the environment. Thus, it combines the proprioceptive capability with the exteroceptive one in a compact form. Furthermore, unlike a force/torque sensor, it does not need expensive calibration. A sensorized passive compliant joint mounted more distally than the last actuated joints on a leg can be automatically recruited as a contact detector. A similar strategy was applied in Ref. [23] where the state of artificial pneumatic muscles was sensed in order to learn about contact of a robotic arm with the environment. Sornkarn *et al.*[24] further quantified the effect of internal impedance on proprioception and accuracy of internal state estimation. Previous case studies in our platform, the Puppy quadruped, studied the role of encoders in the passive compliant knees in speed gauging[25], terrain detection[26,27] and in the information flows in Shannon sense in general[28].

The contribution of the body (the passive compliant joints in particular in this case) to control, sensing and computation has been previously discussed under the term morphological computation[29–31]. This notion can perhaps be further decomposed into (i) morphology facilitating control, (ii) morphology facilitating perception, and (iii) morphological computation[32]. The last subcategory would feature mostly cases where the body is used as a physical reservoir computer[30,33,34]. On the other hand, in this article we will demonstrate the other two aspects (morphology facilitating control and perception) in a single platform.

First, the contribution to control will be investigated. We perform systematic optimization experiments in a simulated version of the robot to shed more light on this process. An automated optimization procedure to find parameters of a minimalistic controller to generate forward locomotion is presented, followed by turning gaits. There, the results are compared against a replica of the robot that is fully actuated, which allows us to directly assess the trade-off that has been postulated in the past — whether underactuation leads to higher energy efficiency while constraining behavioral diversity, such